

Chapter 1: Geotechnical Investigation



Foundation

- A foundation is defined as that part of the structure that supports the weight of the structure and transmits the load to underlying soil or rock. In general, foundation engineering applies the knowledge of geology, soil mechanics, rock mechanics, and structural engineering to the design and construction of foundations for buildings and other structures.

Uses of Foundation Engineering

- Determining the type of foundation for the structure, including the depth and dimensions.
- Calculating the potential settlement of the foundation
- Determining design parameters for the foundation, such as the bearing capacity and allowable soil bearing pressure.
- Determining the expansion potential of a site.
- Investigating the stability of slopes and their effect on adjacent foundations.
- Investigating the possibility of foundation movement due to seismic forces, which would also include the possibility of liquefaction.
- Performing studies and tests to determine the potential for deterioration of the foundation.
- Evaluating possible soil treatment to increase the foundation bearing capacity.
- Investigating groundwater and seepage problems and developing mitigation measures during foundation construction.

Types of foundation

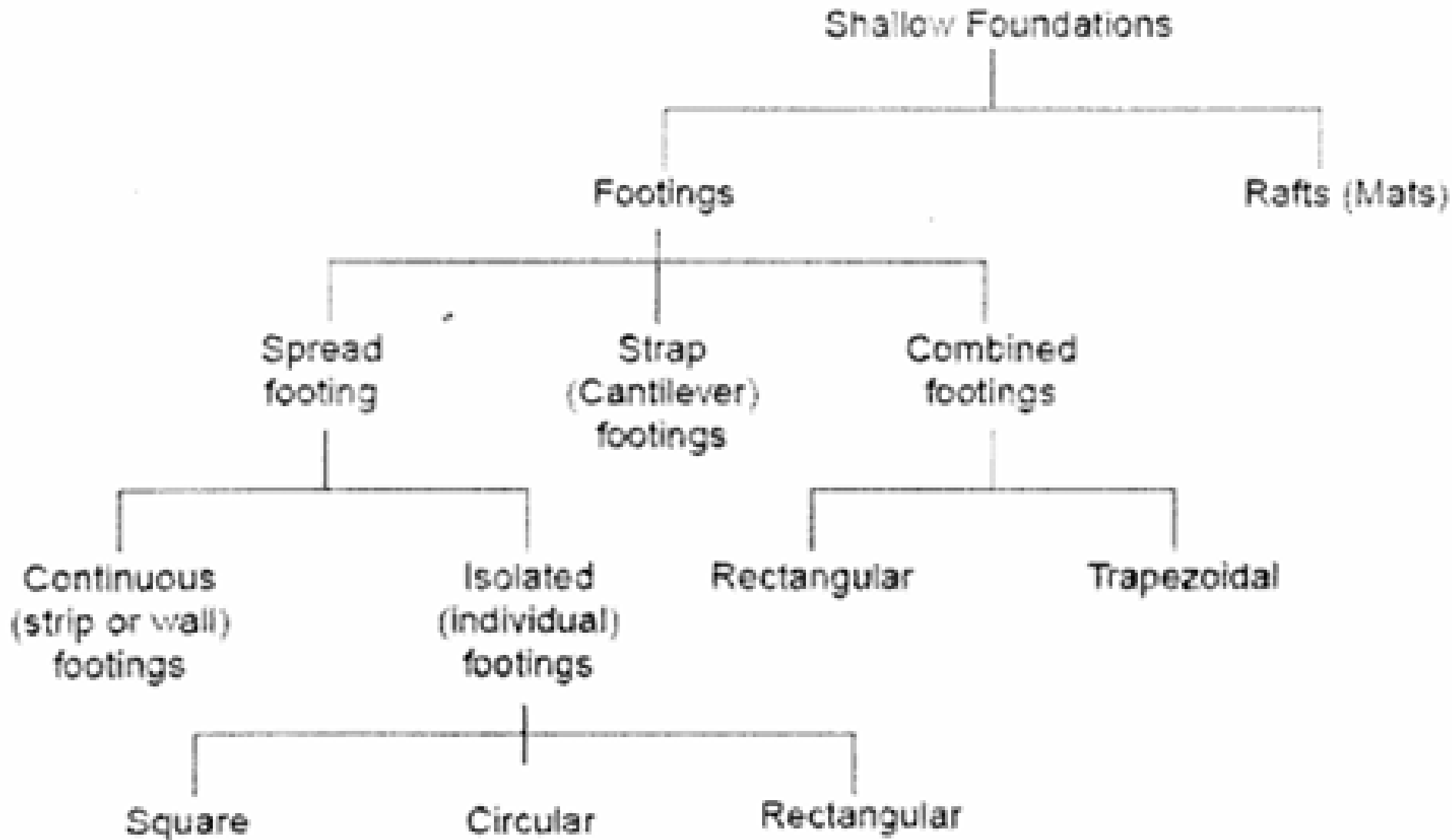
- ❖ Shallow foundation : (D_f/B less or equal to 1)
- ❖ Deep Foundations : (D_f/B , greater than 4)

Where,

D_f = Depth of foundation

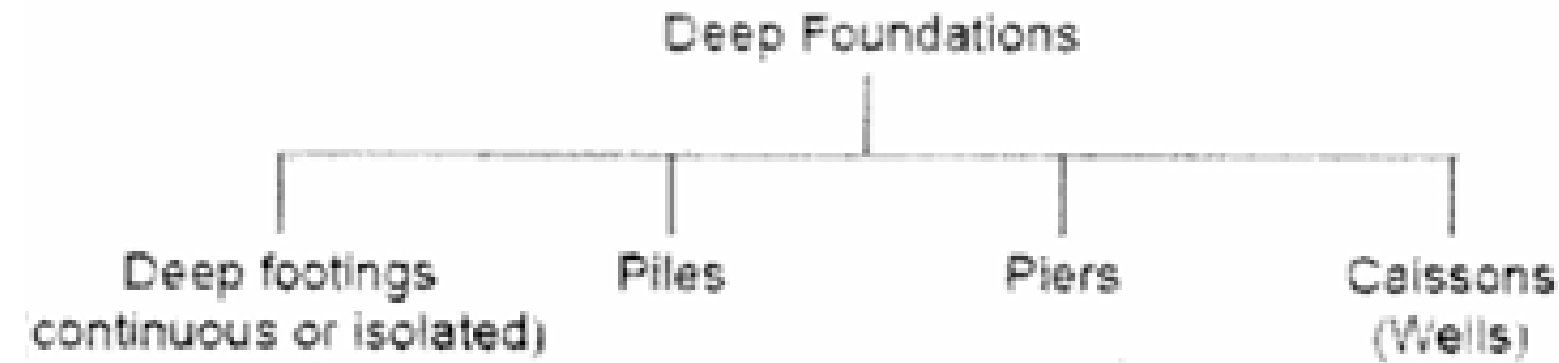
B = Width of foundation

Shallow Foundation



Note:
Homework
Write types
of shallow
foundation
with figure
and its uses

Deep Foundation



Note:
Homework
Write the
types of
deep
foundation
with a figure
and its uses

Factor affecting foundation types

Factor	Description / Effect on Foundation
• Soil properties	• Determines bearing capacity, settlement, stiffness, permeability.
• Groundwater	• Reduces effective stress; causes uplift and seepage issues.
• Load characteristics	• Governs foundation size, depth, and type.
• Environmental conditions	• Earthquakes, frost, flood, and erosion affect safety.
• Site conditions	• Topography and nearby structures influence design options.
• Construction quality	• Poor workmanship causes defects and settlements.
• Depth of foundation	• Must reach strong and stable soil layer.
• Settlement limits	• Ensures structural safety and serviceability.
• Drainage	• Prevents softening and deterioration of soil.

General Requirement of Foundation

- **Adequate bearing capacity**
 - **Minimum settlement**
 - **Uniform settlement**
 - **Stability against sliding**
 - **Stability against overturning**
 - **Safe depth of foundation**
 - **Durability**
 - **Economy**
 - **Proper drainage**
- Soil must safely support all structural loads without shear failure.
 - Total settlement should be within allowable limits.
 - Prevents differential settlement that can cause cracks and tilting.
 - Foundation must resist horizontal forces (wind, seismic loads).
 - Should withstand moments and eccentric loads without rotation.
 - Must be placed below frost level, shrink–swell zone, and loose soil layers.
 - Materials must withstand environmental effects, groundwater, and chemical attack.
 - Should be cost-effective while maintaining safety and performance.
 - Prevents water accumulation that can soften soil and reduce strength.

Selection of Foundation

- **Type of Soil**
 - **Bearing Capacity**
 - **Settlement Characteristics**
 - **Groundwater Level**
 - **Depth of Hard Stratum**
 - **Topography**
 - **Type of Structure**
 - **Construction Constraints**
 - **Cost and Time**
- Strong, dense soils → shallow foundations; weak/compressible soils → deep foundations.
 - High bearing capacity → isolated/strip/raft; low bearing capacity → piles or caissons.
 - Excess settlement → use raft or deep foundation to reduce differential settlement.
 - High water table → prefer pile foundation; avoid open excavations where possible.
 - If competent layer is deep → piles; if near surface → shallow footing.
 - Sloping ground → stepped footings, combined footings, or deep foundations.
 - Low-rise buildings → shallow; towers, chimneys → pile or raft.
 - Limited space or vibration restrictions → bored piles preferred over driven piles.
 - Shallow foundations cheaper and faster; deep foundations costlier but required for weak soils.

1.1 Geotechnical investigation: Objective and scope

- Geotechnical investigation is the process of collecting, analyzing, and interpreting information about the soil, rock, and groundwater conditions of a site to determine its suitability for construction.
- Importance of Geotechnical investigation are
 1. It studies subsurface conditions such as soil type, stratification, strength, and compressibility.
 2. Helps determine bearing capacity, settlement, and stability of the ground.
 3. Involves field tests, laboratory tests, and site reconnaissance.
 4. Ensures the structure is safe, economical, and durable.
 5. Identifies potential problems like liquefaction, expansive soil, soft clay, or high water table.

Components of Geotechnical Investigation

1. Preliminary Investigation

- Collect records, maps, aerial photos, and nearby site data.
- Site visit for surface features, drainage, slope, vegetation, and existing structures.

2. Field Investigation

- Boreholes, trial pits, test pits.
- Field tests: SPT, CPT, Vane shear, plate load test, permeability test.
- Groundwater measurement.

3. Laboratory Testing

- Index tests: Grain size, Atterberg limits, moisture content, density.
- Strength tests: Direct shear, triaxial, unconfined compression.
- Consolidation tests, compaction tests.

4. Reporting

- Soil profile, test results, engineering properties.
- Recommendations for foundation type, depth, bearing capacity, and settlement.

Objective of Geotechnical Investigation

Objective	Description
• Determine subsurface conditions	Identify soil/rock type, stratification, and groundwater conditions.
• Evaluate engineering properties	Assess index, strength, compressibility, permeability, and dynamic properties.
• Assess bearing capacity & settlement	Provide parameters for safe foundation design.
• Identify geotechnical hazards	Detect liquefaction, landslides, swelling soils, collapsible soils, soft layers.
• Provide design recommendations	Suggest suitable foundation type, depth, and ground improvement.
• Ensure safety & economy	Avoid failures, reduce uncertainties, and optimize foundation design.
• Assist construction planning	Support excavation, dewatering, and material quality control

Scope of Geotechnical Investigation

Category

- Desk Study & Preliminary Investigation
- Field Investigation – Drilling & Sampling
- In-situ Tests
- Groundwater Investigation
- Laboratory Testing
- Engineering Analysis
- Reporting

Scope Details

- Review geology, previous reports, aerial images; conduct site reconnaissance.
- Drill boreholes, collect disturbed/undisturbed samples, prepare bore logs.
- SPT, CPT/CPTu, vane shear test, plate load test, permeability tests, geophysical tests (MASW, refraction).
- Measure water table, install piezometers, seasonal monitoring.
- Grain size, Atterberg limits, moisture, density, shear strength (triaxial, DS), consolidation tests, permeability, dynamic tests.
- Bearing capacity, settlement, slope stability, earth pressure, liquefaction assessment, ground improvement design.
- Provide soil profile, test results, engineering parameters, foundation recommendations, construction considerations.

Different stages of exploration

Stage	Purpose	Key Activities
1. Preliminary Investigation	To obtain a general understanding of site conditions and feasibility.	• Desk study (geology, topography, previous reports)
• Site reconnaissance (walk-over survey)		
• Identifying potential hazards (flooding, landslides, soft ground)		
• Planning detailed investigation scope	• Initial site profile	
• Identification of problem areas		
• Preliminary foundation considerations		
• Scope and plan for detailed investigation		

Stage	Purpose	Key Activities
2. Detailed Investigation	To collect accurate engineering data for design of foundations & structures.	• Borehole drilling, trial pits
• Sampling (disturbed & undisturbed)		
• In-situ tests (SPT, CPT/CPTu, Vane shear, Plate load, Packer tests)		
• Geophysical tests (MASW, refraction)		
• Laboratory testing (index, shear strength, consolidation, permeability)	• Soil/rock stratification	
• Engineering parameters (strength, compressibility, permeability)		
• Bearing capacity & settlement analysis		
• Design recommendations (foundation type, depth, improvement methods)		

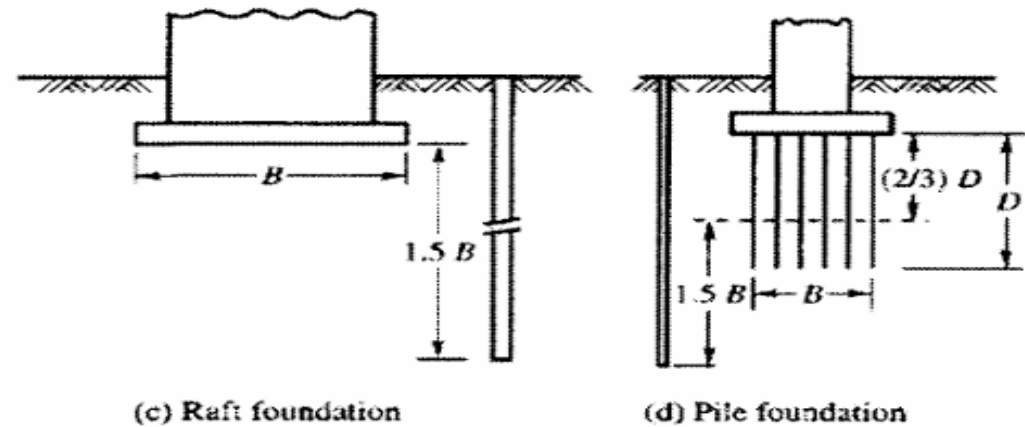
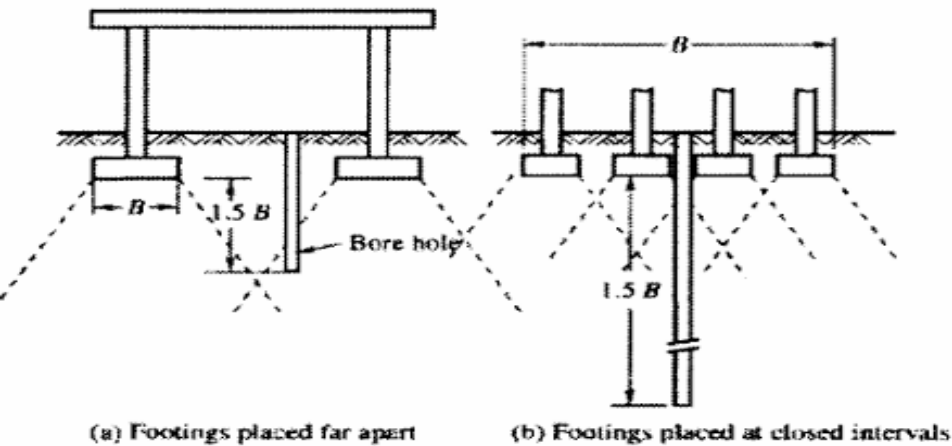
Stage	Purpose	Key Activities
3. During Construction Investigation (Construction Phase Monitoring)	To verify subsurface conditions and ensure design assumptions are correct.	• Field inspection of excavations
• Verification of soil strata vs. bore logs		
• Additional tests if conditions differ		
• Monitoring groundwater inflow		
• Checking compaction quality of fills		
• Adjusting foundation depth if required	• Confirmation/adjustment of design	
• Construction quality control records		
• Identification of unexpected ground conditions		

Stage	Purpose	Key Activities
4. Performance Monitoring (Post-Construction / Operational Stage)	To ensure structure behaves as expected during service life.	• Settlement monitoring (settlement plates, precise leveling)
• Pore pressure monitoring (piezometers)		
• Lateral movement monitoring (inclinometers)		
• Vibration monitoring (for dynamic loads)		
• Long-term groundwater monitoring	• Settlement/time curves	
• Performance evaluation of foundations		
• Detection of long-term issues (creep, consolidation, liquefaction susceptibility)		
• Recommendations for corrective actions if needed		

Extent of exploration

Depth of boring

- ❖ The depth of boring should be equal to the significant depth (Depth upto which superimposed loads can produce significant settlement and shear stresses).
- ❖ Significant depth is generally taken as the depth at which vertical stress is 20% of the load intensity and usually depth of exploration should be about 1.5 times width of footing below the base of footing.
- ❖ Hence depth of boring should be 1.5 times width of square footing.



- ❖ For pile foundations the depth of exploration is 1.5 times width of pile group from tip of piles.
- ❖ For friction pile group the depth of boring should be 1.5 times width of pile group below lower one third length of pile.

For multistoried building the depth of boring can be estimated by following formula given by Sower and Sower (9170).

$$D = CS^{0.7}$$

- ❖ D = Depth of boring (m)
- ❖ C = 3 (for light steel building and narrow concrete building.)
- ❖ = 6 (for heavy steel buildings and wide concrete buildings)
- ❖ S = No. of storey

Lateral extent of explorations:

- ❖ Lateral extent or spacing of boring depends upon the variability of soil strata in the horizontal direction.
- ❖ For small and less important building 1 borehole or the test pit at the centre is sufficient but for compact building on 0.4 hectare, there should be 5 boreholes 1 at the centre and 4 at the corners.
- ❖ For multistoried buildings boring should be done at the 4 corners and other important locations.
- ❖ Lateral extent or spacing of boring depends upon the variability of soil strata in the horizontal direction.
- ❖ For small and less important building 1 borehole or the test pit at the centre is sufficient but for compact building on 0.4 hectare, there should be 5 boreholes 1 at the centre and 4 at the corners.

Infrastructure	Code Reference	Borehole Spacing	Depth of Exploration
Buildings	IS 1892	1 BH per 250–500 m ² ; grid 15–30 m	1.5B or stress <20%; typically 10–20 m
Bridges	IRC:78, IS 1892	1 BH at each pier & abutment	Scour depth × 1.3 + 1.5B
Highways (pavement)	IRC:SP:19, IS 1892	250–500 m	3 m (min), 10–20 m (weak soils)
Embankments	IRC:75, IS 1892	100–200 m	1.5 × embankment height
Railways	IRS Geo Code, IS 1892	250–500 m	3–6 m, up to 20 m for soft clay
Airports	ICAO + IS 1892	250–300 m (runway)	5–10 m (runway), 20–30 m (buildings)

Different Methods of the Site Exploration

- Accessible Methods: Pit/trench
- Inaccessible Methods: Auger Boring, wash Boring, percussion Drilling, rotary Drilling.
- Indirect methods: Seismic Refraction / Reflection, Electrical Resistivity, GPR, Magnetic Survey, SPT, CPT

Accessible Methods

- Accessible methods are simple, economical, easy-to-perform soil exploration techniques that require minimal equipment and can be carried out directly on-site without heavy machinery.
- These methods allow direct access to the soil, meaning the engineer can see, touch, and sample the soil easily.
- Pits and Trenches are examples of accessible methods.

1) Test Pit (Trial Pit)

Definition

Small open excavation (usually 1–1.5 m wide) used to inspect soil at shallow depths.

Typical Depth

Up to 3 m (can go to 5 m with proper shoring).

Purpose

Direct visual inspection, collection of undisturbed samples, locating weak layers or topsoil thickness.

Suitability

Shallow foundations, small buildings, walls, small structures, areas where machinery cannot reach, cohesive or partially cohesive soils.

Advantages

- Direct visual examination of soil
- Best quality undisturbed samples
- Simple, economical for shallow works

Disadvantages

- Limited depth (<3 m normally)
- Collapse risk in loose/wet soils
- Requires shoring beyond 1.5 m depth
- Not suitable for deep foundations

2)Trench

Definition	Long, narrow excavation made to study soil continuity along an alignment.
Typical Depth	Up to 3 m (more with shoring).
Typical Dimensions	Width: 0.8–1.5 m; Length: several metres to 100 m.
Purpose	To observe continuous soil profile horizontally and vertically; assess lateral variation along foundations or linear structures.
Suitability	Highways, railways, canals, pipelines, strip footings, boundary walls, areas where horizontal variation is expected.
Advantages	• Shows a continuous soil profile along the length • Detects changes in soil strata horizontally • Useful for linear projects (roads, canals, pipelines) • Allows multiple sample collection
Disadvantages	• Time-consuming and costlier than test pits • Collapse risk without shoring • Difficult in loose or waterlogged soils • Requires more manpower and space

Inaccessible Methods

- Inaccessible methods are indirect, advanced exploration techniques used where direct excavation or boring is not possible, or soil layers are too deep, difficult, or unsafe to access.
- It requires instruments with deeper reach.
- Auger Boring, Wash Boring, Percussion Drilling, and Rotary Drilling are examples of Inaccessible methods.

Auger Boring

Procedure

- Push and rotate the auger until annular space of auger fills up
- Withdraw the auger and clean it
- Repeat the process

3. Sand Bailer

- Heavy duty pipe with cutting edge
- Lifted and then left to fall freely under self weight. Additional weight (sinker) may be added for ease of sinking

1. Hand Auger

- for shallow depth (3 - 5 m)



2. Power Driven Auger

- for larger depth



Auger Boring

Suitability

- Soft to medium cohesive soils
- Dry soils above water table
- Shallow exploration (up to 10–15 m)
- Buildings, highways, small structures

Advantages

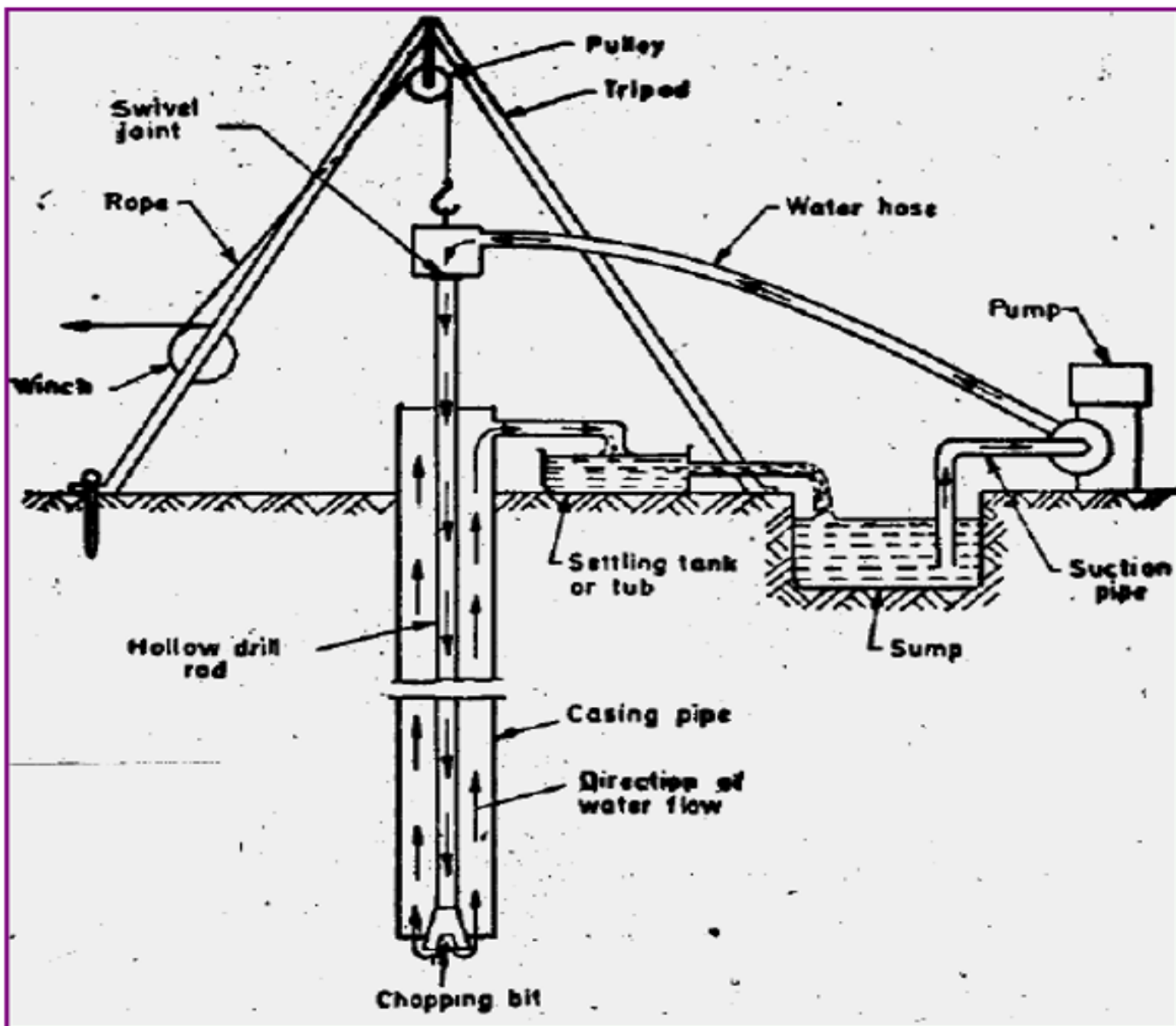
- Simple, quick, economical
- Hand auger needs no heavy equipment
- Continuous soil observation is possible

Disadvantages

- Not suitable below the water table
- Not suitable for gravel, boulders, or hard soils
- Disturbed samples only
- Limited depth of boring

Wash Boring

- A casing pipe of 2-3 m length is driven into the soil by a heavy drop hammer.
- The soil inside the casing is removed by means of a chopping bit attached to a drill rod which forces water at high pressure.
- Soil mixed with water moves up in annular gap between drill rod and casing.
- Samples are obtained at certain depth by removing drill rod and pushing a sampler instead.



Wash Boring

Suitability

- Soft to medium clays, loose sands, silts
- Waterlogged areas
- Depth up to 30 m
- Good for bridges, deep foundations

Advantages

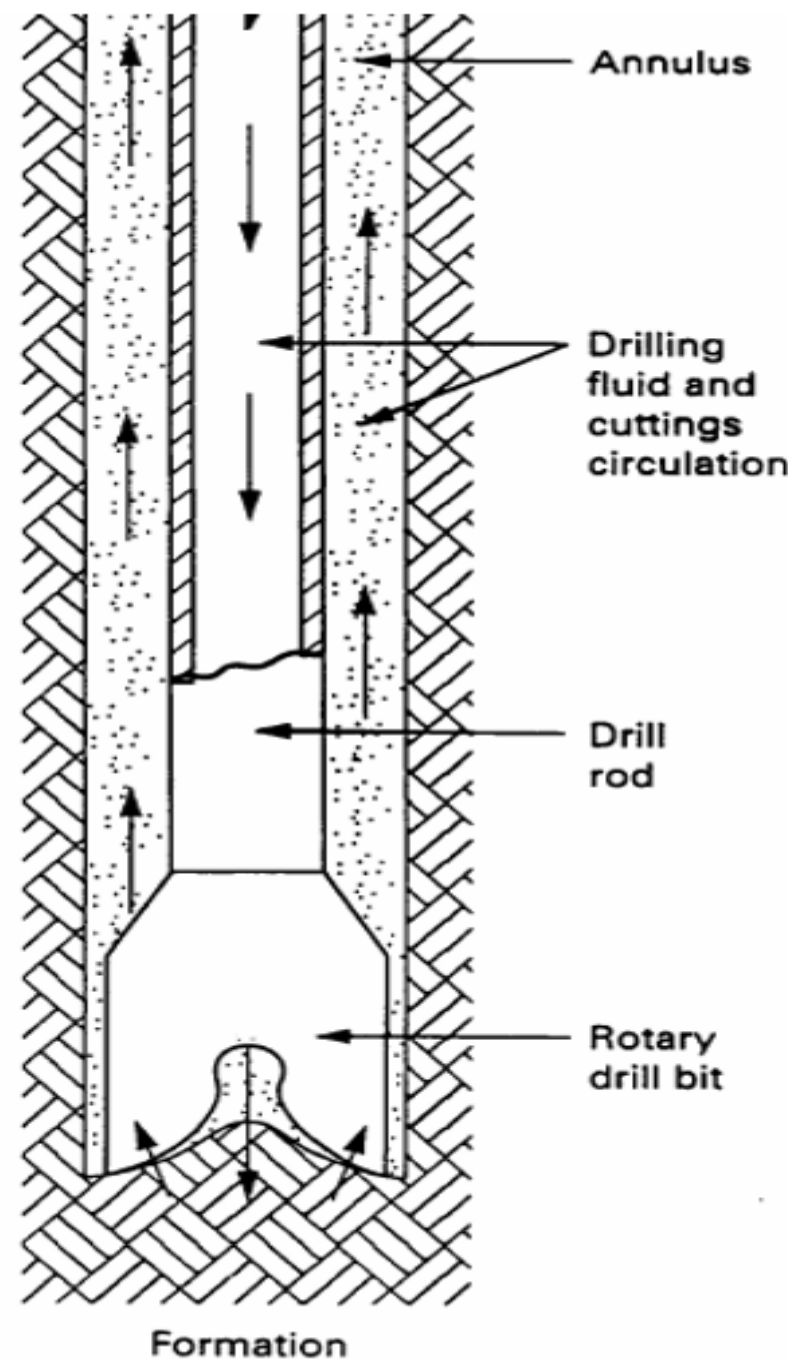
- Inexpensive for deeper soils
- Simple equipment
- Works well below the groundwater table
- SPT can be conducted easily in a wash borehole

Disadvantages

- Soil structure is destroyed → **no undisturbed sample**
- Not suitable for hard soils or gravels
- Slow in stiff/hard clays
- Cannot identify exact strata thickness due to slurry mixing

Rotary Drilling

- Design similar to wash boring
- Useful when soil is resistant to augering or wash boring
- Boring is done by rapidly rotating drilling bits attached to bottom of drilling rod.
- Soil/rock cuttings removed by circulating drilling fluid
- Samples are taken at certain depths by removing drill rod and placing sampler.
- Mud Rotary Drilling: Hollow drilling rods are used to flow mud slurry (Bentonite) to check caving in of the material (soil) at bottom.
- Core Drilling: Core barrels with diamond bit are used.



Rotary Drilling

Suitability

- All types of soils and rocks
- Deep exploration (50–200 m)
- Hard strata, boulders, rock cores
- Dams, tunnels, major bridges, high-rise buildings

Advantages

- Fastest deep drilling method
- Can penetrate hard soil and rock
- Rock core recovery is excellent
- Accurate identification of layers
- Works under all groundwater conditions

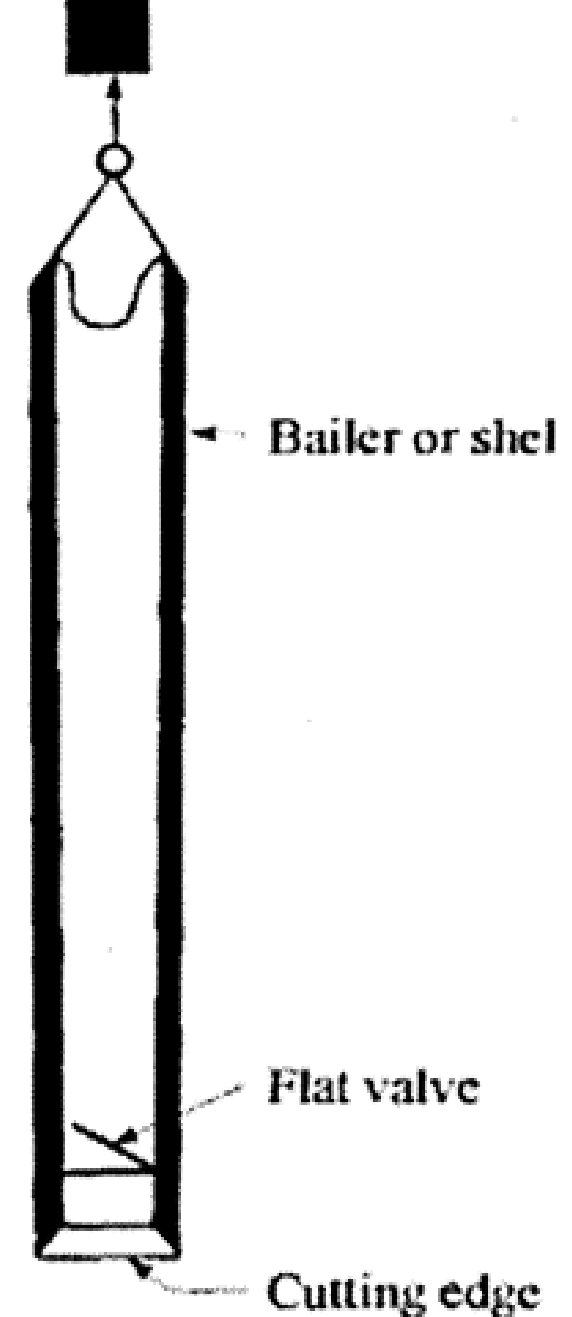
Disadvantages

- Expensive equipment and operation
- Skilled operator needed
 - Not economical for small projects
- Requires heavy machinery and space

Percussion drilling:

- ❖ Grinding the soil by repeated lifting and dropping of heavy chisels or drilling bits.
- ❖ Water is added to form slurry of cuttings.
- ❖ Slurry removed by bailers or pumps.
- ❖ In general, a machine used to drill holes is called a drill rig (generally power driven, but may be hand driven).

A winch is provided to raise and lower the drilling tools into the hole.



Percussion Drilling

Suitability

- Hard soils, stiff clays, gravels, boulders
- Rocky strata
- Deep drilling (20–80 m)
- Foundation investigation for heavy structures

Advantages

- Can break hard soil and boulders
- Works in difficult soils where auger/wash fails
- Low-maintenance equipment
- Suitable for deep groundwater table areas

Disadvantages

- Slower than rotary drilling
- Soil gets disturbed → poor sample quality
- Water circulation is needed for removing cuttings
- Cannot provide continuous rock cores

Indirect Methods

- Indirect methods are subsurface exploration techniques in which soil and rock properties are estimated without directly excavating or sampling the ground.
- They rely on measurements of soil response, such as penetration resistance, wave velocity, or electrical properties, rather than direct visual inspection.

Indirect Methods

Method	Principle	What It Detects	Suitability	Advantages	Disadvantages
Seismic Refraction / Reflection	Wave velocity differences	Bedrock depth, layer stiffness, fractures	Dams, bridges, tunnels, deep profiles	Fast for large areas; good depth penetration	Poor in loose, saturated soils; requires expertise
Electrical Resistivity	Electrical resistance	Water table, clay vs sand, cavities	Dams, foundations, groundwater studies	Good for groundwater and clay detection	Limited in dry sand; field setup time
GPR	EM wave reflection	Pavement layers, utilities, voids	Highways, airports, urban sites	Rapid, high-resolution shallow imaging	Limited depth; ineffective in clay
Magnetic Survey	Magnetic field variation	Buried metal, faults	Pipelines, utilities, geology	Fast and simple	Only detects magnetic materials
Gravity Survey	Density differences	Cavities, deep soft zones	Large geological studies	Covers large areas	Poor resolution; expensive

Soil Sampling

- **Disturbed Samples:** Natural soil structure is modified or destroyed during sampling
 - **Representative Samples:**
 - Natural water content and mineral constituents of particular soil layer are preserved
 - Good for soil identification and water content
 - **Non-representative Samples:**
 - Water content altered and soil layers mixed up
 - Of no use.
- **Undisturbed Samples:** Soil structure and the other mineral properties are preserved to an extent.
 - Some disturbance is always there, e.g. due to stress release. However it should be minimized in order to have suitable sample for our analysis.

Aspect	Disturbed Sample	Undisturbed Sample
Structure preserved?	✗ No	✓ Yes
Cost	Low	High
Ease of collection	Easy	Difficult
Typical samplers	Auger, SPT spoon	Shelby tube, piston sampler
Used for classification tests?	✓ Yes	✓ Yes
Used for strength tests?	✗ Generally No	✓ Yes
Used for compressibility tests?	✗ No	✓ Required
Suitable for compaction tests?	✓ Yes	✗ Not needed
Main purpose	Soil identification	Design-critical engineering properties

Soil Sampler

- A soil sampler is a device used in geotechnical investigation to collect soil samples from below the ground surface for laboratory testing and classification.
- The purpose of a soil sampler is to obtain soil that represents the in-situ conditions in terms of structure, density, moisture, and composition.
- Depending on the requirement, soil samplers are designed to collect either disturbed or undisturbed samples.

Requirement of Soil Sampler

Requirements of a sampler

- ❖ Cutting edge properly machined and taper should not exceed 20 degree.
- ❖ The tube should be seamless and should be round without any protrusions.

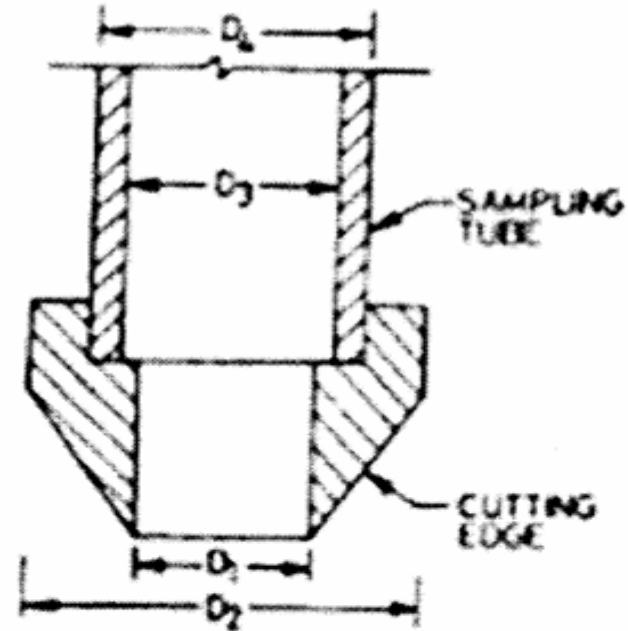
Area ratio:

A_r = Maximum cross sectional area of cutting edge * 100 %
area of soil sample

$$A_r = \frac{D_2^2 - D_1^2}{D_1^2} \times 100$$

D_1 = Inner diameter of cutting edge

D_2 = Outer diameter of cutting edge



Thicker the wall, greater the disturbance. Obtaining good quality of undisturbed sample, the area ratio should be 10% or less.

A_r may be as high as 30% for a thick wall sampler like split spoon and may be as low as 6 to 9% for thin wall samplers like shelly tubes.

Inside clearance ratio

$$C_i = \frac{D_3 - D_1}{D_1} \times 100$$

Inside clearance allows elastic expansion of the sample when it enters the tube which helps to reduce frictional drag on the soil sample from the wall of the tube.

For undisturbed soil sample the inside clearance ratio should be between 0.5 to 3%.

Outside clearance ratio:

$$C_o = \frac{D_2 - D_4}{D_4} \times 100$$

Outside clearance ratio facilitates in withdrawal of sampling tube.

For reducing driving force, the outside clearance ratio should be between 0 to 2% for cohesive soils and preferably zero for cohesionless soil.

Recovery ratio:

$$R_r = \frac{\text{Length of core recovered}}{\text{Length of core drilled in a given run}}$$

- $L_r < 1 \rightarrow$ Compression
- $L_r > 1 \rightarrow$ Swelling
- $L_r \approx 1 \rightarrow$ No change, Good recovery

Soil Sampler Types

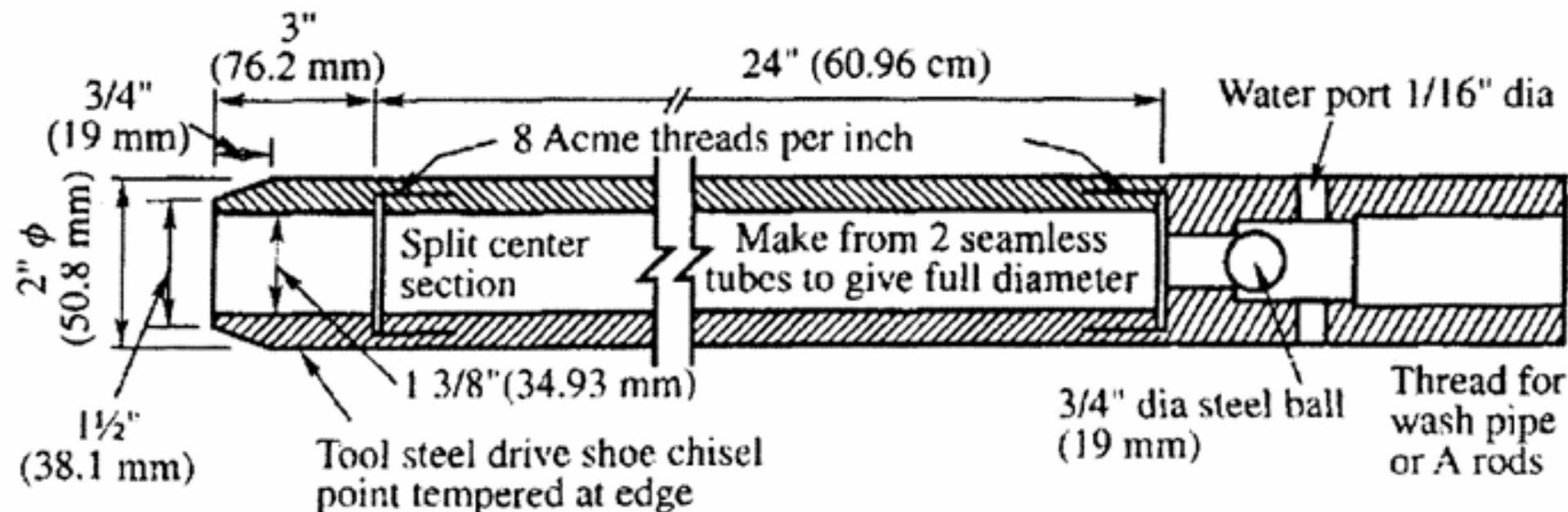
1. Split spoon sampler
2. Scraper bucket sampler
3. Thin sampler(Shelby Tube)
4. Piston Sampler

Split spoon sampler

The split spoon sampler is most commonly used sampler used to obtain disturbed samples in all types of soils.

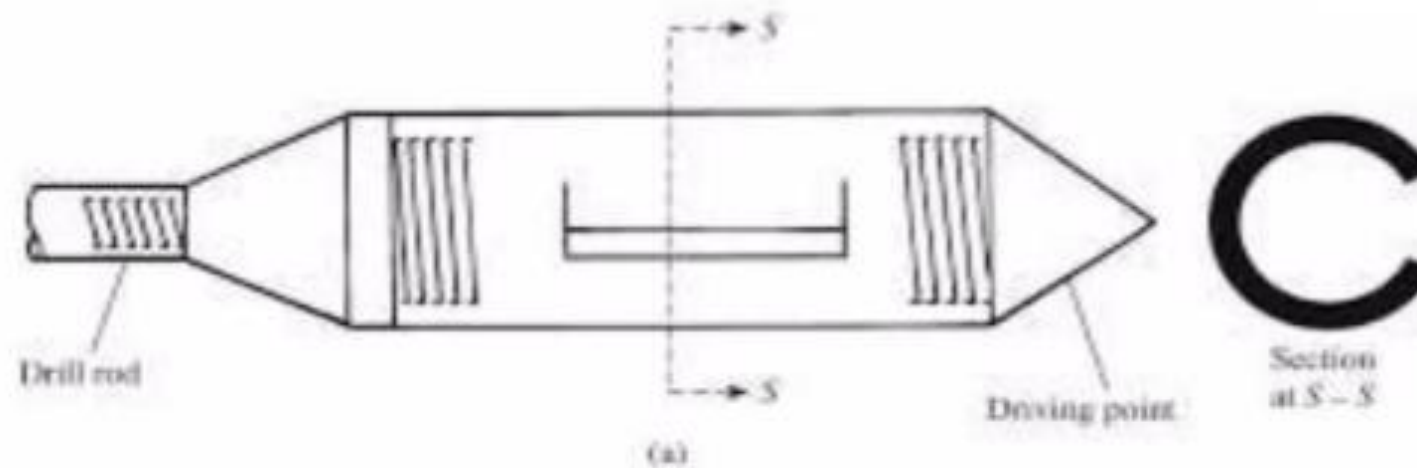
It mainly consists of 3 parts i) Driving shoe, made of tool- steel, about 75mm long ii) steel tube about 450mm long, splits into two halves iii) coupling at the top about 150mm long. The inside and outside diameter of split tube are 38mm and 50mm.

It is used in conjunction with standard penetration test (SPT), attached to drill rod.



Scraper bucket sampler

- ❖ In sandy deposits containing pebbles, it is not possible to obtain samples by split spoon sampler.
- ❖ A scraper bucket sampler consists of a driving point which is attached to its bottom end and a vertical slit in the upper portion of the sampler.
- ❖ As the sampler is rotated, the scrapings of the soil enter the sampler through slit. When the sampler is filled with the scrapings, it is lifted and sample is withdrawn.
- ❖ The samples obtained by this sampler are quite disturbed but representative.

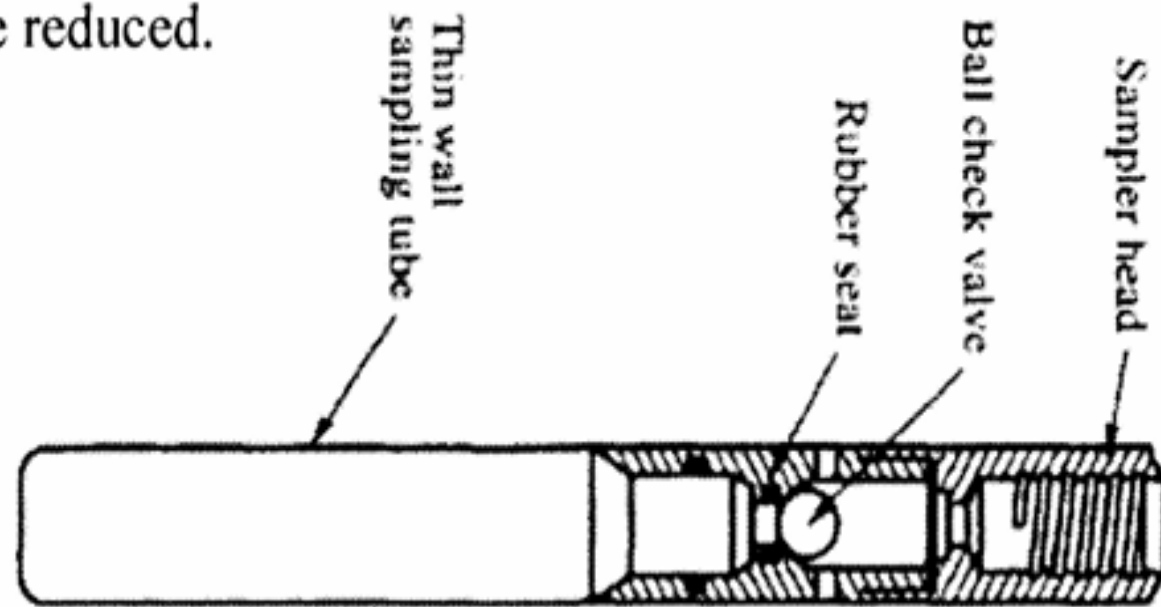


Sampling devices: (a) scraper bucket

Thin walled sampler (Shelby)

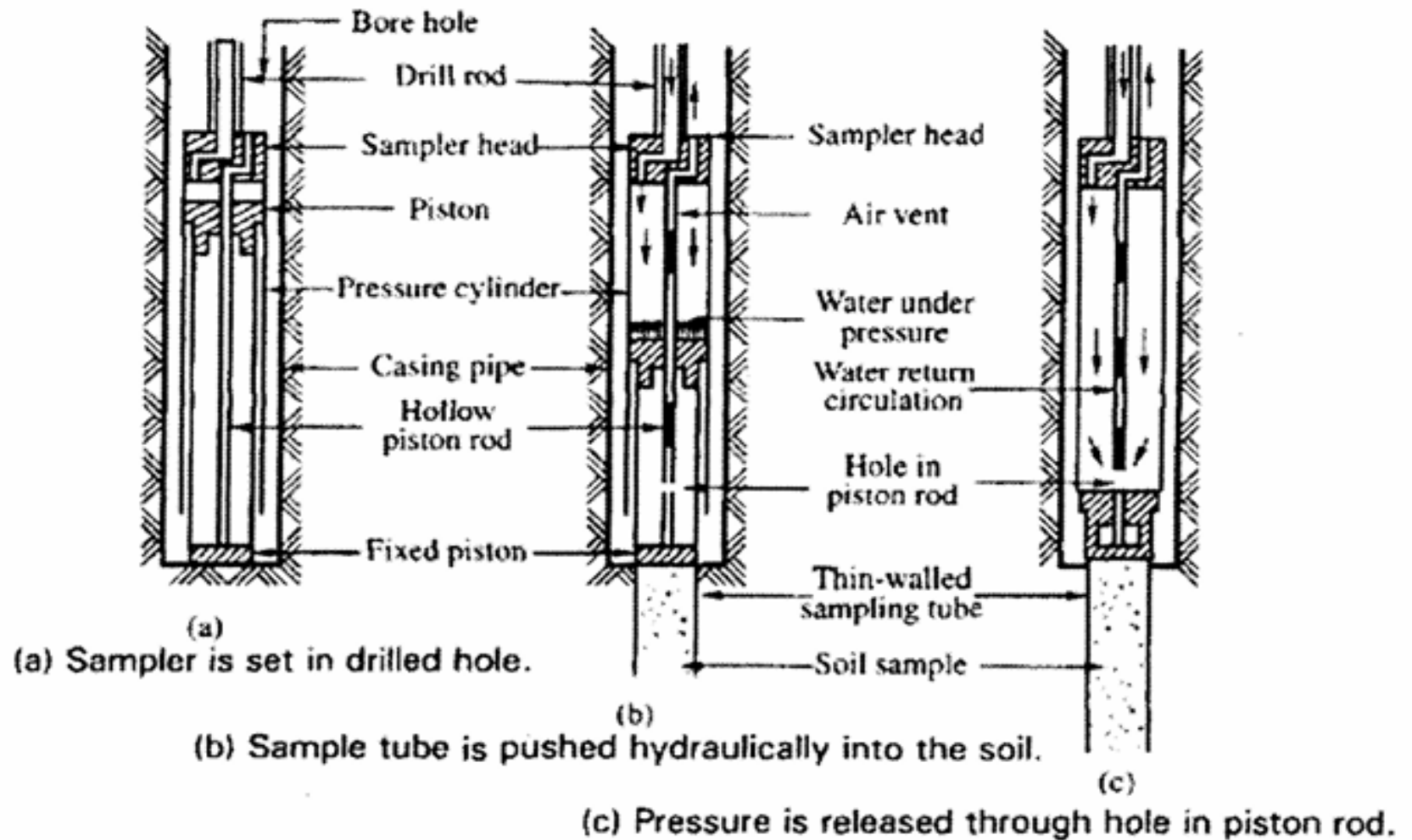
- ❖ The thin walled tube (Shelby) sampler is commonly used to obtain relatively undisturbed samples of cohesive soils for strength and consolidation testing.
- ❖ They are made up of seamless steel with bottom sharpened and beveled and then pushed into the soil.
- ❖ The sampler is commonly used has 76mm outside and 73mm inside dia. And area ratio is less than 15% and inside clearance between 0.5% to 3%.

Larger dia. Sampler tubes are often used where higher quality samples are required and the sampling disturbance must be reduced.



Piston sampler

- ❖ A piston sampler is basically a thin wall tube sampler with piston, piston rod, and a modified soil sampler head.
- ❖ Piston keeps the lower end of the sampling tube closed when the sampler is lowered to the bottom of the hole.
- ❖ The presence of the piston prevents rapid squeezing of the soft soils into the tube and reduces the disturbance of the sample.
- ❖ A vacuum is created on the top of the sample, which helps in retaining the sample.
- ❖ Piston samplers are used for getting undisturbed soil samples from soft and sensitive clays.
- ❖ From this sampler 100% recovery of sample is enhanced.

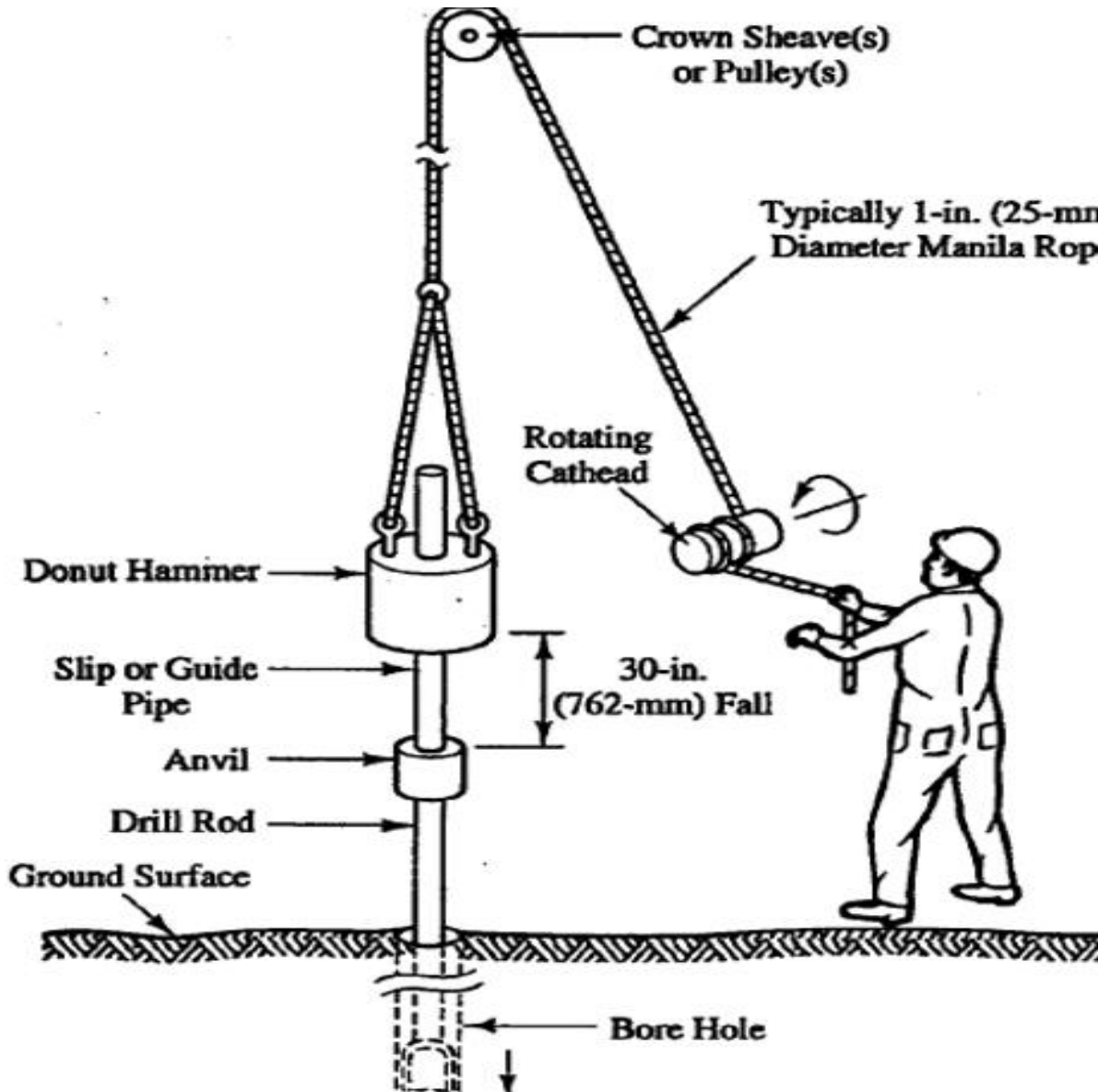


Osterberg Piston Sampler

Field tests

- Standard penetration test (SPT)
- Cone penetration test (CPT)
- Dynamic cone penetration test (DCPT)
- Pressure meter tests (PMT)
- Dilatometer tests (DMT)

Standard Penetration Test (SPT)



■ Components

□ Drilling Equipment

- Inner diameter of hole → 100 to 150 mm
- Casing may be used in case of soft/non-cohesive soils

□ Split spoon sampler → IS:9640-1980

□ Drive weight assembly

- Falling Weight = 63.5 Kg
- Fall height = 76 cm

□ Others → Lifting bail, Tongs, ropes, screw jack, etc.

■ Procedure

- The bore hole is advanced to desired depth and bottom is cleaned.
- Split spoon sampler is attached to a drill rod and rested on bore hole bottom.
- Driving mass is dropped onto the drill rod repeatedly and the sampler is driven into soil for a distance of 450 mm. The number of blow for each 150 mm penetration are recorded.

■ Procedure (Cont....)

□ N-value

- First 150 mm penetration is considered as seating penetration
- The number of blows for the last two 150 mm penetration are added together and reported as N-value for the depth of bore hole.

- The split spoon sampler is recovered, and sample is collected from split barrel so as to preserve moisture content and sent to the laboratory for further analysis.
- SPT is repeated at every 750 mm or 1500 mm interval for larger depths.
- Under the following conditions the penetration is referred to as refusal and test is halted
 - a) 50 blows are required for any 150 mm penetration
 - b) 100 blows are required for last 300 mm penetration
 - c) 10 successive blows produce no advancement

SPT Correction

- Corrected SPT value

$$N_{1,60} = (N * C_N * C_E * C_B * C_R * C_S) / 0.6$$

- SPT below corrected against 1 Atm and 60% hammer efficiency

Correction	Symbol	Purpose
Energy	(C_E)	Standardize to 60% energy
Overburden	(C_N)	Normalize for confining stress
Rod Length	(C_R)	Standardize rod energy loss
Borehole Diameter	(C_B)	Correct for large holes
Sampler	(C_S)	Adjust for liner presence

SPT Corrections

Correction for Overburden Pressure :

$$N' = C_N \cdot N$$

N' = Corrected value of observed N

C_N = Correction factor for overburden pressure

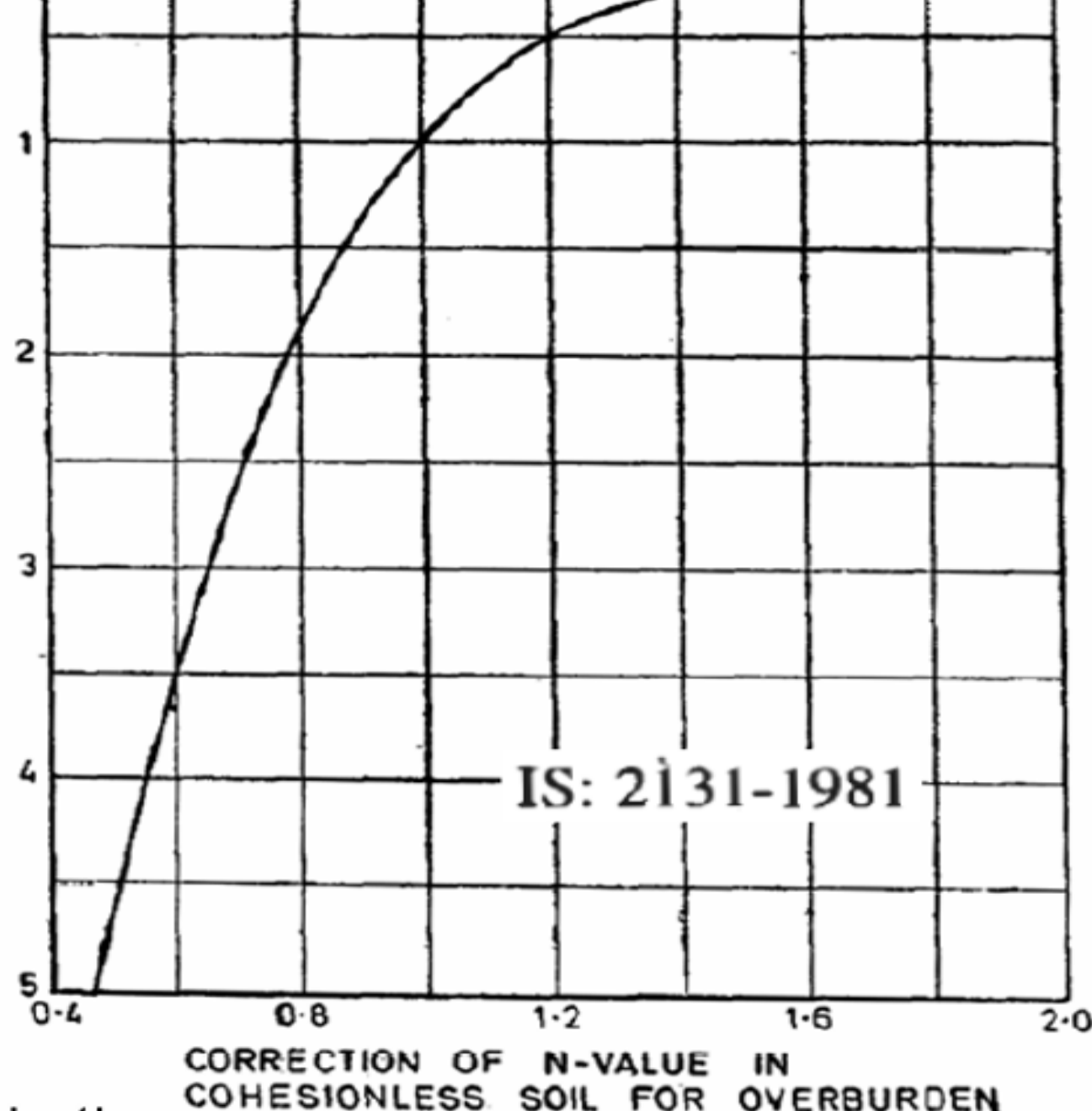
Peck, Hanson and Thornburn (1974)

$$C_N = 0.77 \log_{10} \frac{20}{\bar{p}} \text{ in kg/cm}^2$$

$$C_N = 0.77 \log_{10} \frac{2000}{\bar{p}} \text{ in kN/m}^2$$

p' = Effective overburden pressure at a depth corresponding to N -value measurement

EFFECTIVE VERTICAL OVERBURDEN
PRESSURE kgf/cm^2



Correction for Overburden Pressure : (Alternative)

Bazaraa (1967).

$$C_N = \frac{4}{1 + 4\bar{p}} \quad \text{if } \bar{p} \leq 0.75 \text{ kg/cm}^2$$

$$C_N = \frac{4}{3.15 + 4\bar{p}} \quad \text{if } \bar{p} > 0.75 \text{ kg/cm}^2$$

Correction for Dilatancy :

If the stratum consists of fine sand and silt below water table, for $N' > 15$, the dilatancy correction is applied as

$$\left[\begin{array}{l} N'' = 15 + 0.5 (N' - 15) \quad (\text{when } N' > 15) \\ \text{If } N' \leq 15, N'' = N' \end{array} \right] \leftarrow \text{IS: 2131-1981}$$

Alternative -

Bazaraa (1967). $\longrightarrow N'' = 0.6 N'$ for $N' > 15$.

Application of SPT

S.N.	Application	Use of SPT	Formula
1	Soil Classification	Estimate relative density & consistency	Relative Density (Dr) for sand: $D_r(\%) = 15\sqrt{N}$ (approx.) Consistency of clay: Soft ($N < 4$), Medium (4–8), Stiff (8–15), Very stiff (> 15)
2	Shear Strength Parameters	Estimate ϕ of sand and c of clay	Angle of friction (ϕ) (Peck et al.): $\phi = 27.1 + 0.3N - 0.00054N^2$ (for clean sand) Undrained shear strength (S_u): $S_u = 5N$ (kPa) (for clays)
3	Elastic Moduli (E, G)	Estimate deformation properties	Young's modulus (E): $E = (2.5 \text{ to } 4) N \times 10^3$ kPa Shear modulus (G): $G = (0.5 \text{ to } 1) N \times 10^3$ kPa
4	Bearing Capacity	Determine allowable bearing pressure	Meyerhof correlation: $q_a = N \times 40$ (kPa) Terzaghi & Peck: $q_{net} = 12 N$ (kPa) (for footings at 1 m width)
5	Settlement Estimation	Immediate & consolidation settlement	Schmertmann modulus (E_s): $E_s = (15 \text{ to } 20) N$ (MPa) Settlement: $S = \frac{qB(1-\nu^2)}{E_s} \cdot I_s$

Factors affecting SPT value:

- ❖ Height of fall of monkey hammer
- ❖ Interference of drop hammer by guide rod
- ❖ Diameter and Condition of Winch
- ❖ Number of Turns of rope in winch
- ❖ Condition of rope
- ❖ Improper seating of sampler in the bottom of the hole
- ❖ Effect of isolated stone met in the hole
- ❖ Effect of water table in silts and fine sands

Suitability

- Suitable for granular soils (sand, silty sand, gravelly sand).
- Works for medium to stiff clays (gives approximate strength & stiffness).
- Suitable for deep boreholes during subsurface exploration.
- Used for bearing capacity, settlement, liquefaction, and pile design correlations.
- Applicable for depths up to 30–50 m.

Merits

- Simple, fast, and low-cost field test.
- Requires minimal equipment and skill.
- Provides N-value, which relates to density, consistency, shear strength, and stiffness.
 - Works well in granular soils, where tube sampling is ineffective
- Many empirical correlations available worldwide (bearing capacity, settlement, liquefaction).

Demerits

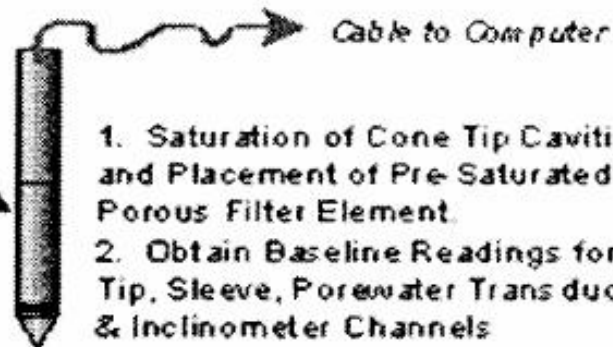
- Results are empirical and approximate.
- Not reliable in very soft clay, gravel, cobbles, or bouldery layers.
- Influenced by borehole diameter, rod length, hammer efficiency, and operator variability.
- Less accurate compared to CPT.

Static Cone penetration test (CPT):

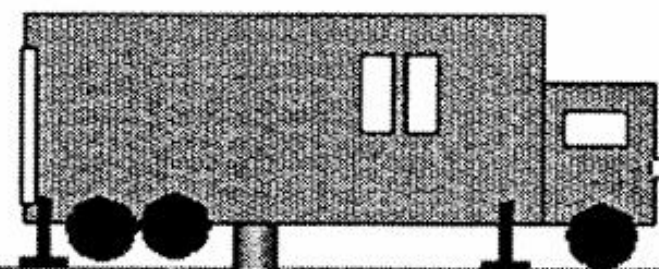
Cone Penetration test (CPT):

- ❖ CPT is an in situ test which has been proved valuable for soil profiling.
- ❖ History: Introduced nearly 50 years ago in Holland and Belgium (introduced by soil mechanics laboratory at Delft).
- ❖ Due to this reason static cone penetration test is also referred as Dutch cone penetration test.

Electric Cone Penetrometer
with 60° Apex:
 $d = 36 \text{ mm}$ (10 cm^2)
or
 $d = 44 \text{ mm}$ (15 cm^2)

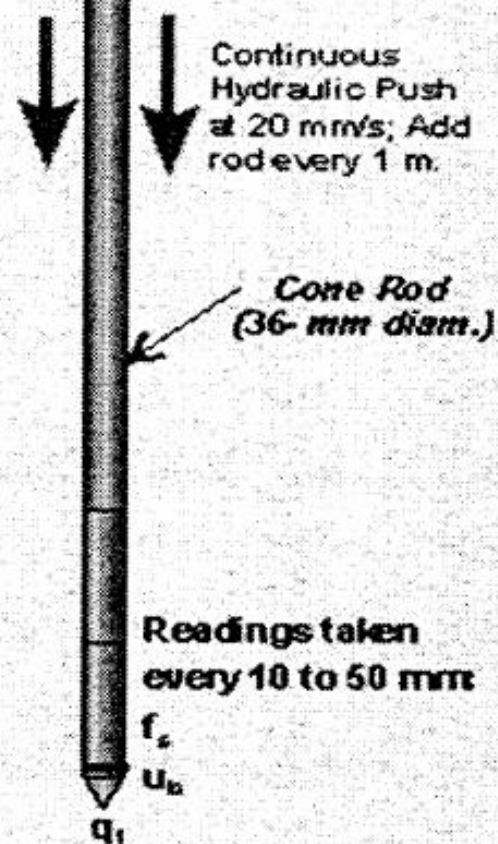
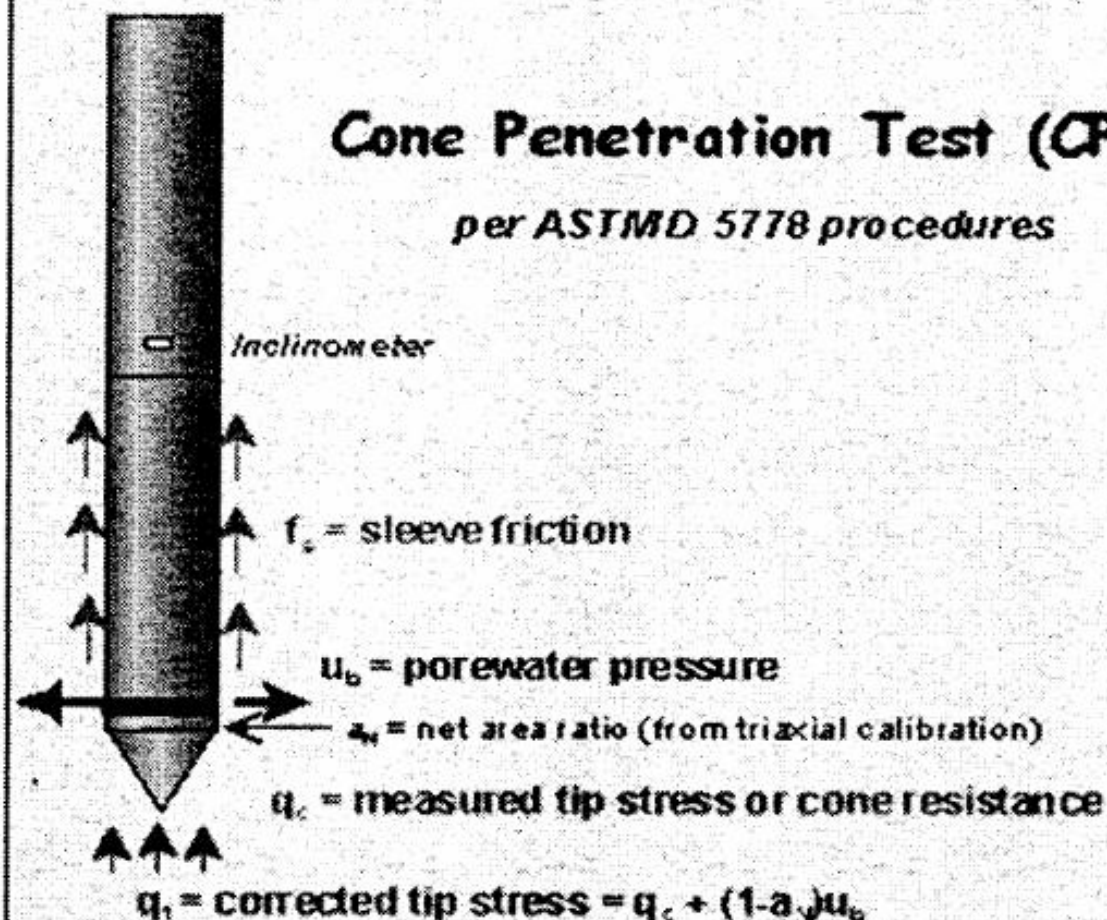


1. Saturation of Cone Tip Cavities and Placement of Pre-Saturated Porous Filter Element.
2. Obtain Baseline Readings for Tip, Sleeve, Porewater Transducer, & Inclinometer Channels



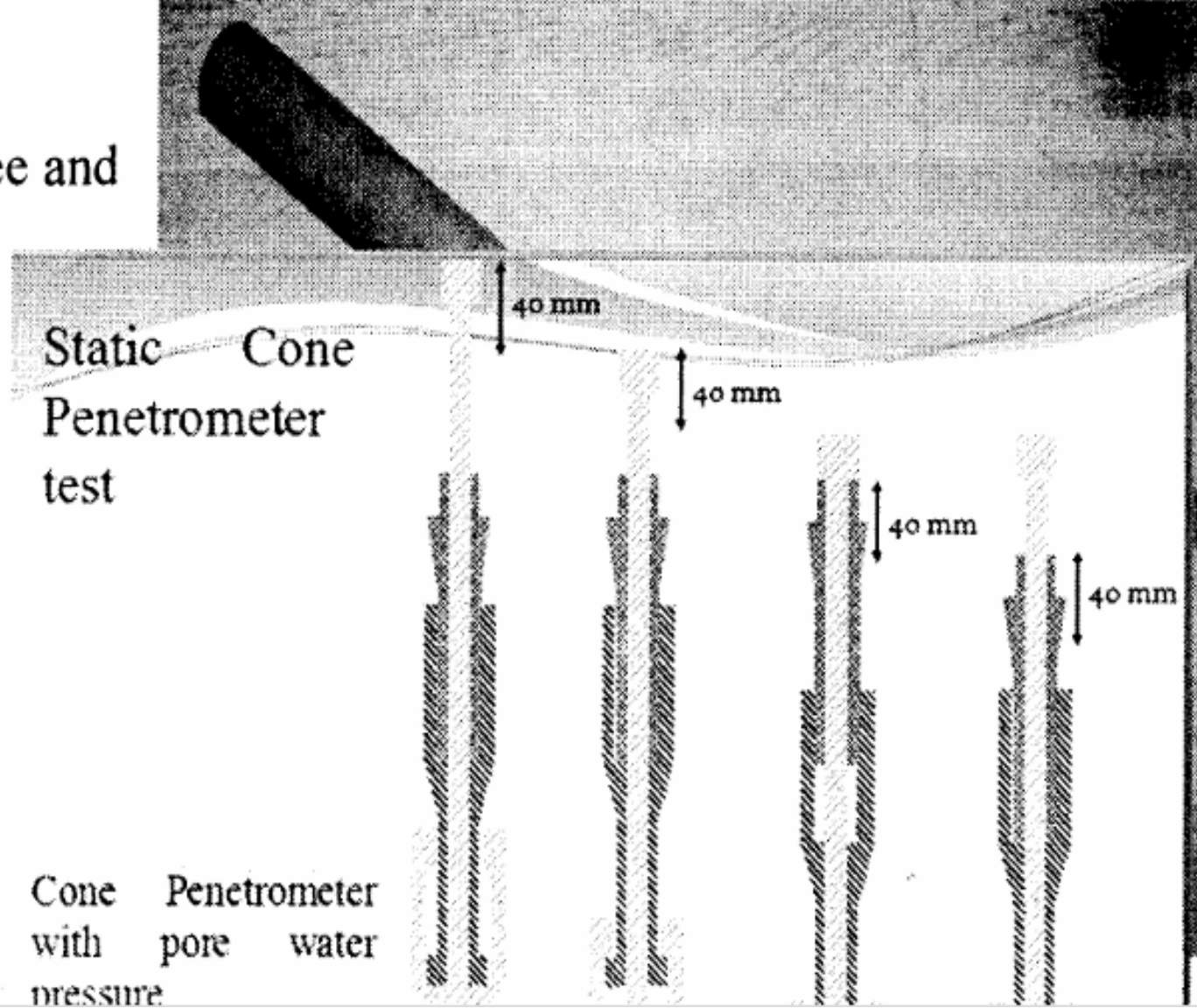
Cone Penetration Test (CPT)

per ASTM D 5778 procedures



Static cone penetration test:

- ❖ Dutch cone has an apex angle of 60 degree and overall diameter of 35.7mm giving an end area of 10 cm^2 .
- ❖ Cone and jacket are pushed at the standard rate of 10mm per seconds and for the depth of 40mm at a time.
- ❖ The cone is pushed downwards by applying the thrust.
- ❖ Resistance offered by cone and sleeve are measured individually by burden



gauges provided in the driving mechanism.

- ❖ Also called Dutch cone penetration test.
- ❖ The cone is pushed continuously into the ground and automatic measurements are taken of the force on the tip and sleeves
- ❖ Depth is also recorded
- ❖ Cone resistance q_c and friction resistance f_s are used together with charts to obtain soil parameters

PENETROMETER

- ❖ 60° cone
- ❖ Base area = 10 cm²
- ❖ Diameter of cone = 35.7mm
- ❖ Frictional sleeve = 15 cm²

Suitability

- ❖ In coarse grained soils.
- ❖ CPT is very functional (useful) in small scale pile load model test.

Force required for the inner rod to push the tip (Q_c) and the total force required to push both the tip and the sleeve ($Q_c + Q_f = Q_t$) will be measured

$$q_c = \frac{Q_c}{A_c}$$

In the same way, the local side friction f_c is

$$f_c = \frac{Q_f}{A_f}$$

where, $Q_f = Q_t - Q_c$ = force required to push the friction jacket,

Q_t = the total force required to push the cone and friction jacket together in the case of a mechanical penetrometer,

A_f = surface area of the friction jacket.

Friction ratio, R_f is expressed as

$$R_f = \frac{f_c}{q_c}$$

Various correlations have been developed to determine soil strength parameters (c , ϕ , etc) from R_f

The relation between q_c and undrained shear strength C_u of a clay:

$$q_c = N_k C_u + \sigma_0$$

where,

σ_0 = total overburden pressure

N_k = Cone factor, taken as 20 in general

Use of friction ratio for soil classification:

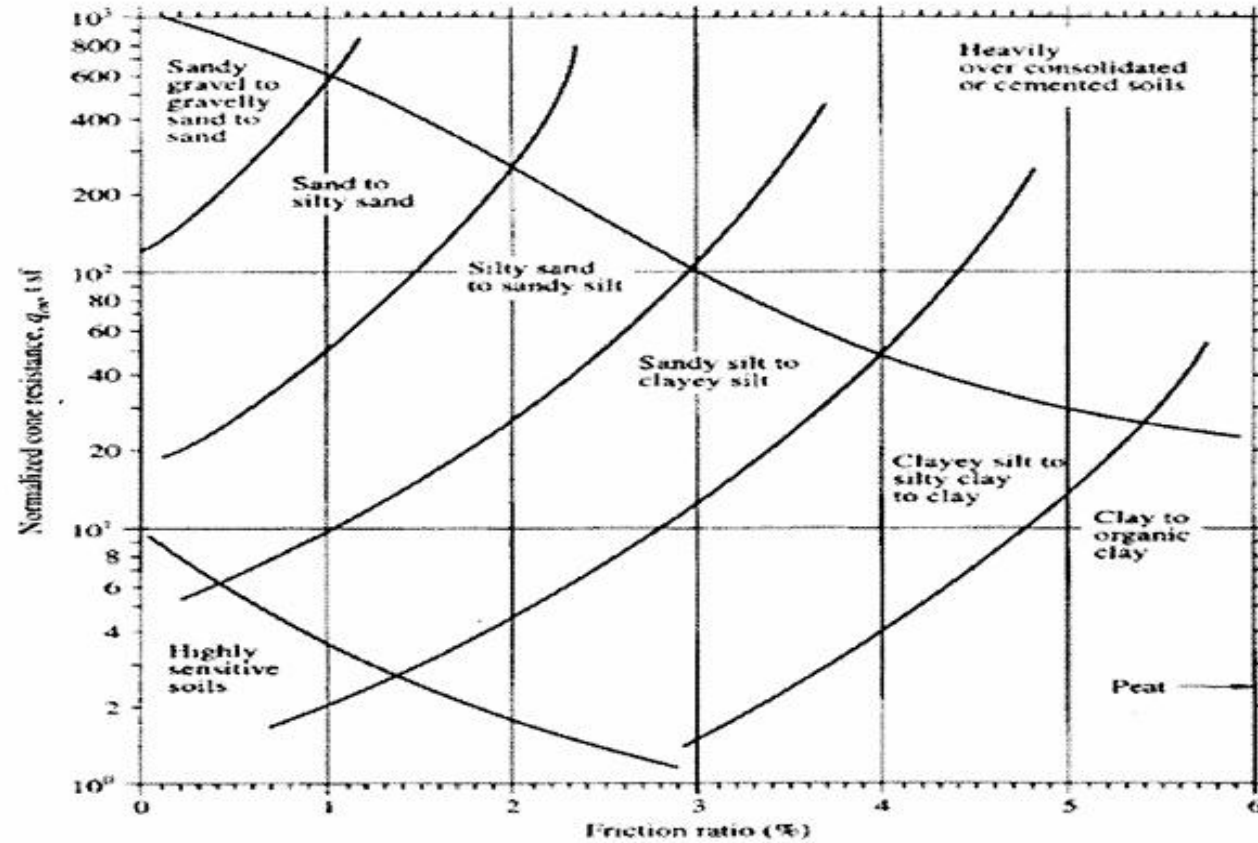


Figure 9.16 A simplified classification chart (Douglas, 1984)

Co-Relation with q_c and N :

- ❖ Sands $q_c = 500$ N to 600N
- ❖ Silty Sands $q_c = 300$ N to 400N
- ❖ Silts and clayey soil $q_c = 200$ N
- ❖ Where q_c is in KN/m^2 .

Applications

- Soil stratification – identifies layers and thickness accurately.
- Soil classification – clay, silt, sand, using CPT charts.
- Geotechnical properties – S_u , ϕ , D_r , OCR, E, G.
- Bearing capacity – shallow and pile foundations.
- Settlement estimation – compressibility and stiffness.

Merits

- Continuous data with depth → more accurate than SPT.
- Fast, efficient, economical for large projects.
- Less operator-dependent → repeatable and reliable.
- Multiple parameters measured simultaneously (q_c , f_s , u_2).
- Excellent for soft soils where SPT fails.

Demerits

- Cannot penetrate gravel, cobbles, boulders, or very dense layers.
 - Requires specialized equipment → higher cost.
- Does not provide soil samples (no visual identification).
- Requires a skilled operator and proper interpretation.

Dynamic Cone penetration test (DCPT):

Dynamic CPT

- ❖ It can be Dry or wet-DCPT.
- ❖ Test is conducted by driving the cone by blows of hammer.
- ❖ Number of blows for driving the cone through a specified distance is the measure of the dynamic cone resistance (N_{cbr}).

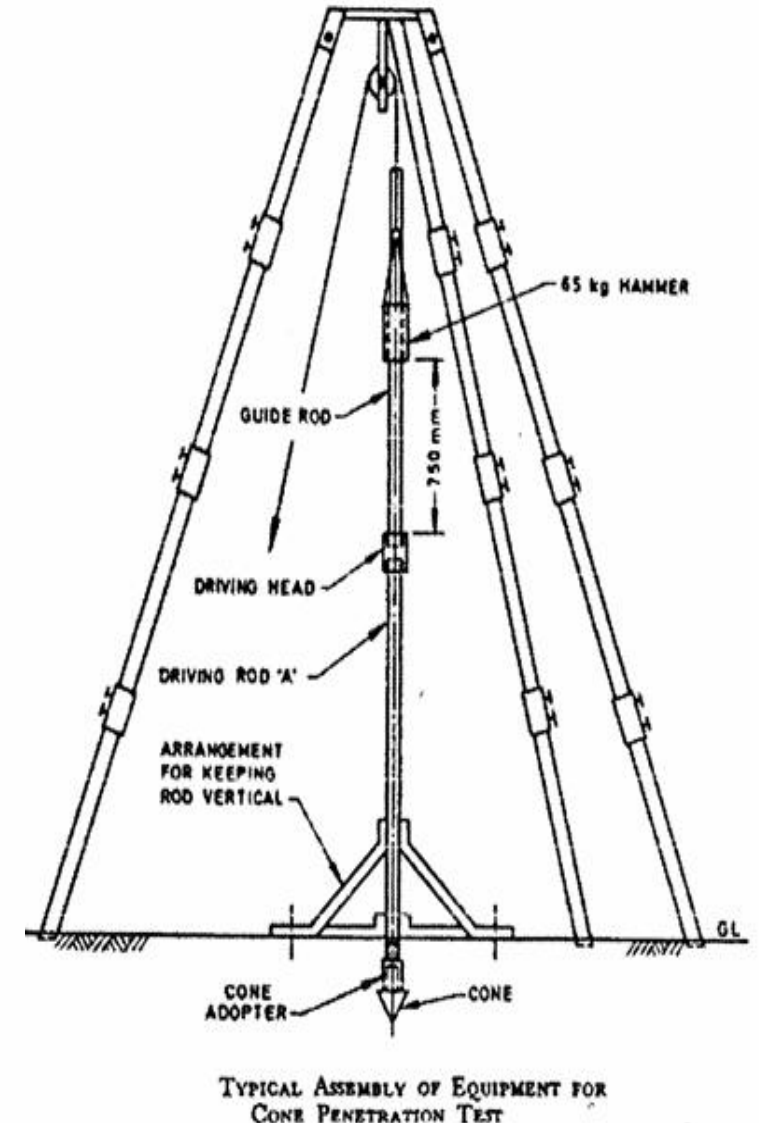
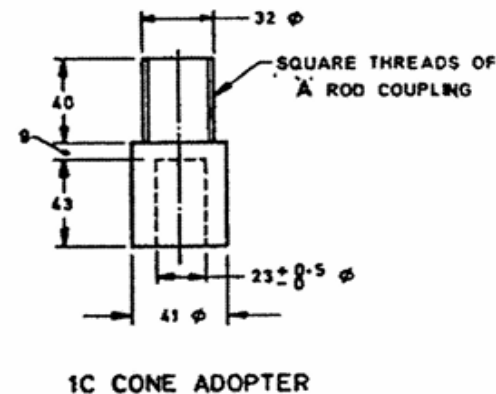
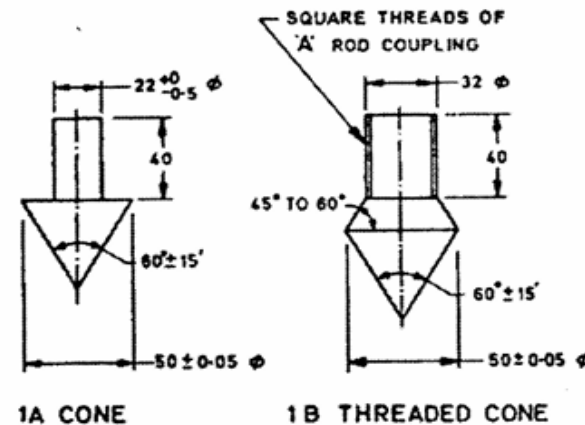
Dry DCPT (Without using bentonite slurry)

- ❖ 50mm cone without bentonite slurry used in cased borehole to eliminate skin friction.
- ❖ Driving energy- 65kg hammer falling through 75cm.
- ❖ The number of blows required for 30cm of penetration is taken as cone penetration resistance (N_{cbr}).

Co-Relation with SPT(N):

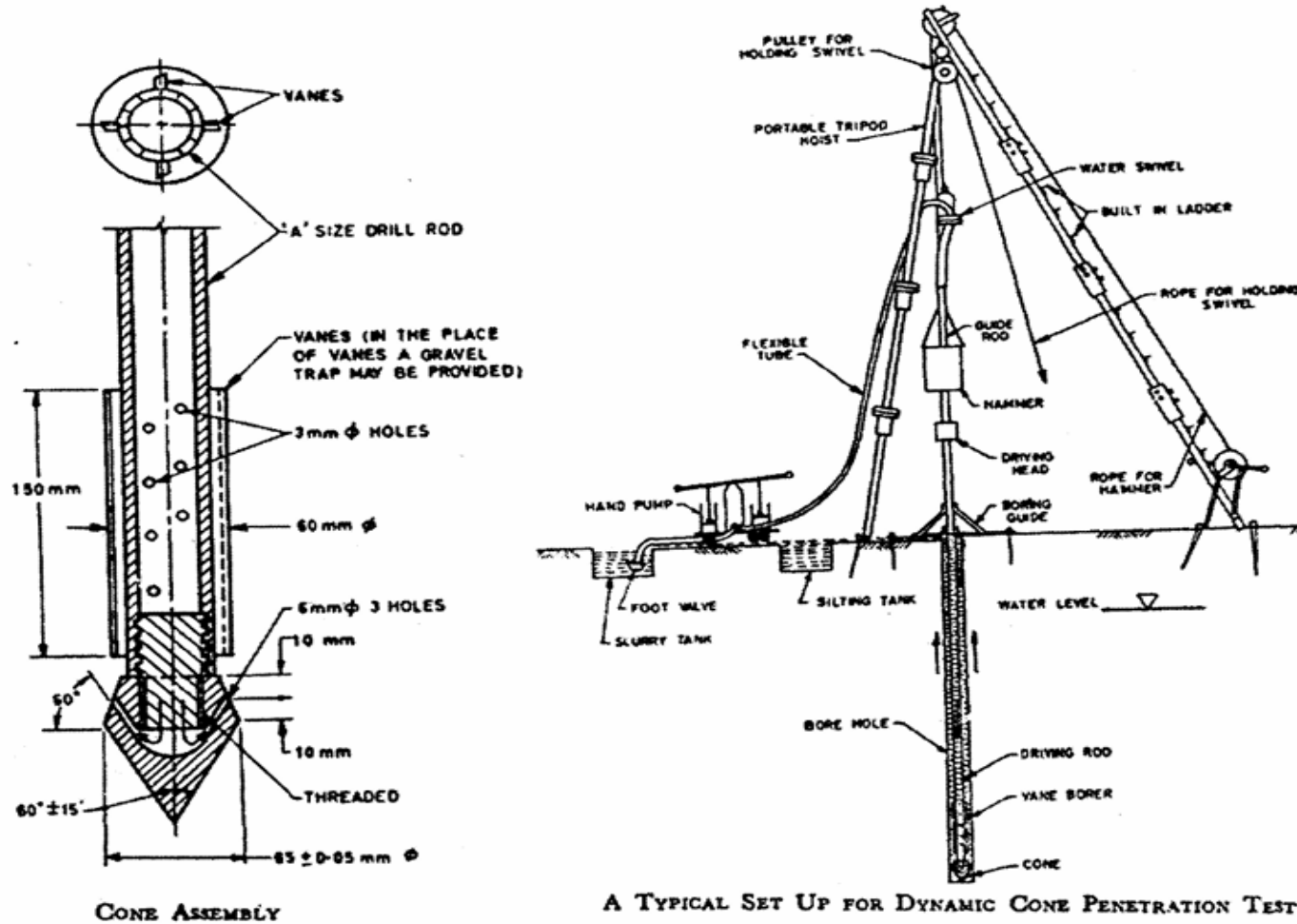
For 50mm cone

- ❖ $N_{cbr} = 1.5N$ (For depths upto 3m)
- ❖ $N_{cbr} = 1.75N$ (for depth greater than 3-6m)
- ❖ $N_{cbr} = 2N$ (for depth greater than 6m)



Wet DCPT:

- ❖ 62.5 mm (65 mm cone has been withdrawn as per IS code) with bentonite slurry at the end of drill rod with arrangement for drilling mud to flow through the cone as shown in fig.
- ❖ Conducted to eliminate frictional resistance on the drilling rods.



When the 62.5mm cone is penetrated by circulating slurry.

$$N_{cbr} = N$$

- For medium to fine sands, the above relationships have been developed by the central Building Research Institute, Roorkee.
- These relationships, when utilized, shall be used with caution.

As Per IS : 4968 (Part I & II) – 1976, the correlation between cone penetration value (N_{cbr}) and standard penetration value (N)

When the 62.5mm cone is driven up to 9m (without bentonite slurry)

$$N_{cbr} = 1.5 N \text{ – for depth upto 4m}$$

$$N_{cbr} = 1.75 N \text{ – for depth between 4 – 9m}$$

Suitability

- Suitable for near-surface soil investigation (up to 6–10 m depth).
- Works for granular soils, sandy soils, silty soils, and soft clays.
- Not suitable for very dense gravel, boulders, or highly stiff clays.
- Ideal for pavement subgrade evaluation and road/base layer assessment.

Applications

- Soil strength estimation
- Subgrade assessment
- Layer thickness measurement – identify weak/soft layers.
- Preliminary geotechnical surveys – quick field screening.

Merits

- Simple, rapid, and low-cost field test.
 - Portable equipment → can be used in remote or restricted areas.
- Provides immediate results.
- Useful for road and pavement subgrade evaluation.

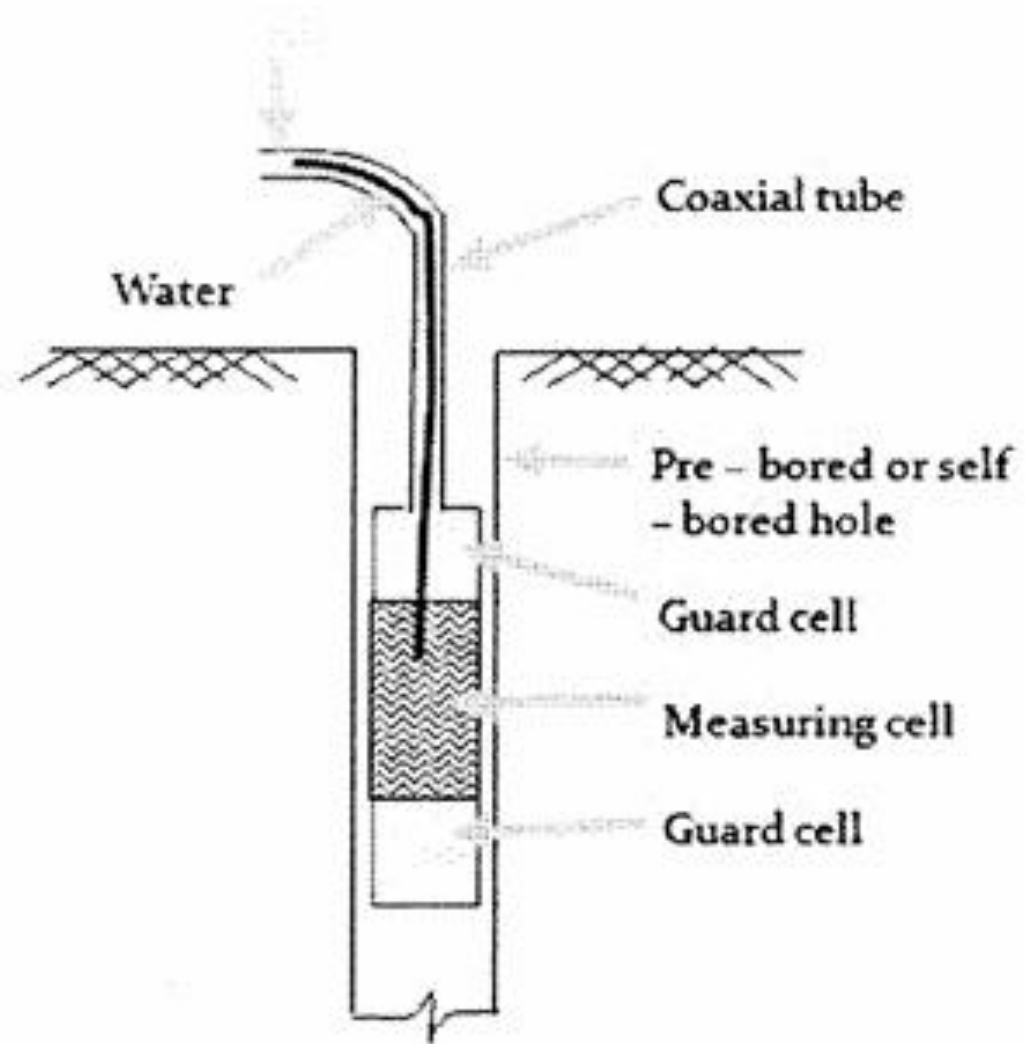
Demerits

- Only suitable for shallow investigations (limited depth).
- Provides approximate results, not very precise for design.
- Cannot provide soil samples for lab testing.
- Not suitable for stiff, very dense, or bouldery soils.

Pressuremeter tests (PMT)

Parameter	Pressuremeter Test (PMT)
Definition	In-situ test where a cylindrical probe is inserted into a borehole and soil is horizontally loaded by expanding a flexible membrane to measure deformation.
Equipment	• Pressuremeter probe (Menard/Prebored type) • Control unit with pressure-volume recorder • Gas/water pressurization system • Calibration tools • Borehole drilling tools
Procedure	1. Drill a borehole to the required depth. 2. Insert the pressuremeter probe into the borehole. 3. Inflate the membrane in increments. 4. Record pressure-volume curve. 5. Determine limit pressure, Menard modulus, and yield pressure.

Pressuremeter



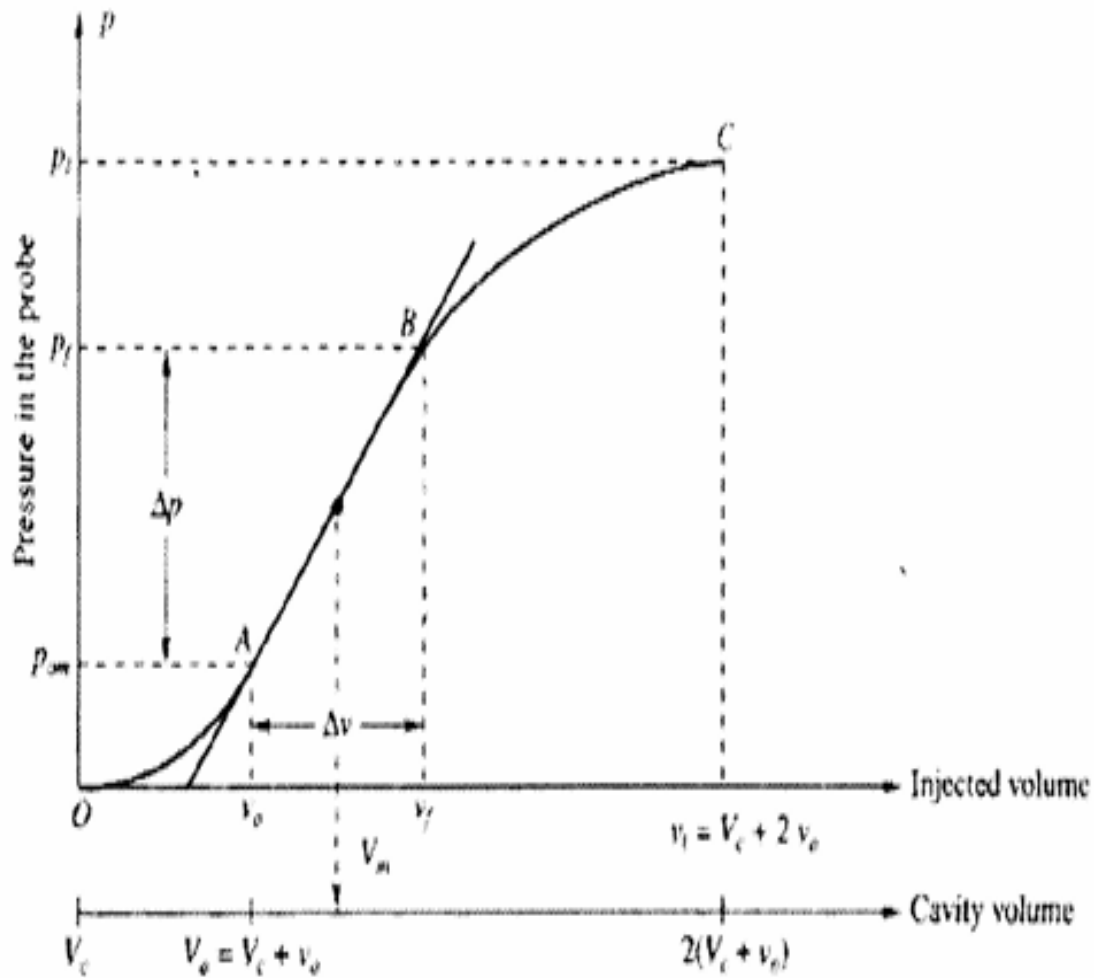


Figure 9.20 A typical corrected pressuremeter curve

Graph Interpretation

- ❖ Zone I- Represents reloading portion during which the soil around the borehole is pushed back into the initial state (i.e., the state it was before drilling)
- ❖ The pressure P_0 represent the initial total horizontal stress.
- ❖ Zone II – Represents a **pseudo elastic zone** in which the cell volume verses cell pressure is practically **linear**.
- ❖ Zone III – The **plastic zone** P_L represents the limit pressure
- ❖ P_0 =Lift off pressure , P_f = Yield pressure , P_L = Limit pressure

Correlations from PMT:

- ❖ Shear modulus 'G'
- ❖ Undrained shear strength 'Cu'
- ❖ Coefficient of earth pressure at rest 'Ko'

$$E_p = 2G_s(1 + \mu) = 2(1 + \mu)V_m \frac{\Delta p}{\Delta v}$$

where G_s is the shear modulus.

Pressuremeter Modulus:

$$V = V_m = V_c + \frac{v_0 + v_f}{2},$$

μ_s = Poisson's ratio, assumed as 0.33

$$E_m = 2.66V_m \frac{\Delta p}{\Delta v}$$

Suitability	• Cohesive & cohesionless soils • Soft to stiff clays • Loose sands • Weathered rock • Deep foundation design • Determining settlement and bearing capacity
Merits	• Provides direct in-situ stress-strain curve • Very reliable modulus (Menard modulus) • Suitable from soft clay to weathered rock • Excellent for design of piles, rafts, caissons • Less disturbance compared to sampling
Demerits	• Requires borehole → costly & time-consuming • Skilled operator needed • Unsuitable in very loose sand (collapse) • Equipment expensive • Interpretation complex

Dilatometer tests (DMT)

Definition	Flat plate test where a stainless steel membrane is expanded against soil to measure deformation and stiffness.
Equipment	• Marchetti dilatometer blade • Pneumatic control unit • Pressure gauge • Gas cylinder/compressor • Rods for pushing blade (cone rig / CPT rig)
Procedure	1. Push DMT blade into soil using CPT rig. 2. At testing depth, inflate the membrane. 3. Take readings: A-pressure (contact), B-pressure (expansion), C-pressure (closing). 4. Compute soil modulus, strength, and in-situ stresses.

Calibrations of Membrane
Stiffness in Air:
 $\Delta A = 10$ to 30 kPa (suction)
 $\Delta B = 30$ to 80 kPa (inflate)
Note: both positive values

Incremental
Hydraulic Push
at 20 mm/s, Stop
to test every 200
mm (or 300 mm)

Tubing

Gage

N_2

Readout
Panel and
Gas Supply

Cone or
Drill Rod

Pneumatically-
inflated Flexible
Steel Membrane
($d = 60$ mm)

Flat Plate
Dilatometer
Tapered Blade
 95 mm wide
by 240 mm long
by 15 mm thick

1. Initial

Membrane
collapsed
due to soil
stresses

2. Push

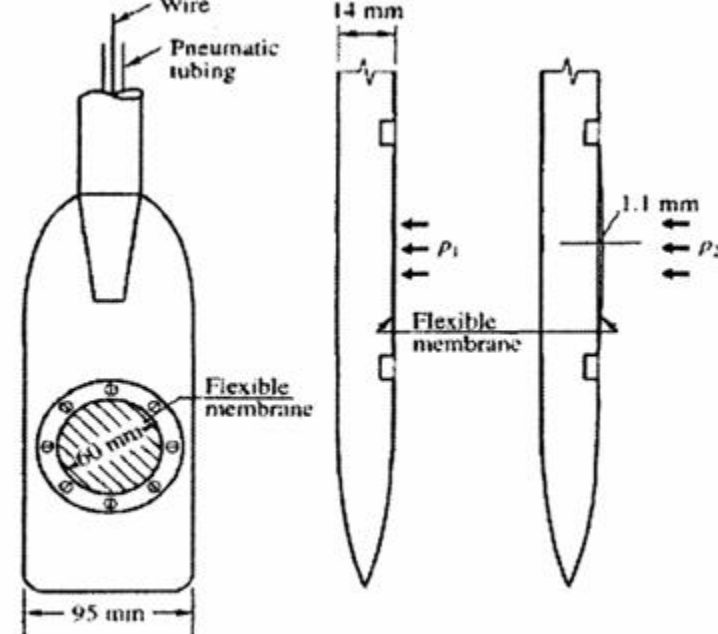
Membrane
push

3. A-reading

Membrane
expanded
outward 1.1 mm

4. B-reading

5. Deflate Rapidly



Plan or Face View

Profile Views

FLAT DILATOMETER TEST (DMT)

p_0 = Lift-off pressure (corrected "A" reading)

p_1 = Expansion pressure (corrected "B" reading)

The details of the calculation lead to the following equations:

1. Material index, $I_D = \frac{p_2 - p_1}{p_2 - u}$

2. The lateral stress index, $K_D = \frac{p_1 - u}{p'_o}$

3. The dilatometer modulus, $E_D = 34.7(p_2 - p_1) \text{ kN/m}^2$

where, $p'_o = \text{effective overburden pressure} = \gamma'z$

$u = \text{pore water pressure equal to static water level pressure}$

$\gamma' = \text{effective unit weight of soil}$

$z = \text{depth of probe level from ground surface}$

Suitability	• Soft to medium clays • Silts & sands • Shallow to medium-depth investigation • Pavement subgrade evaluation • Liquefaction potential assessment
Merits (Advantages)	• Quick and economical • No borehole required (pushed like CPT) • Good repeatability & consistency • Provides horizontal stress index • Useful for settlement & stiffness prediction • Works well in soft to firm soils
Demerits (Disadvantages)	• Cannot penetrate gravel or hard soils • Requires CPT pushing system • Membrane damage possible • Limited depth (typically <40 m) • Interpretation semi-empirical

Groundwater observation

- Groundwater observation is essential to determine the depth of the water table, seasonal fluctuation, pore water pressure, and subsurface flow conditions during site investigation.
- It helps determine the groundwater table, pore water pressure, and seasonal changes that affect soil strength and stability.
- It is done using open boreholes, standpipe piezometers, vibrating wire piezometers, and observation wells.
- These instruments allow engineers to monitor how the groundwater level rises or falls over time.

S.N Importance of Groundwater Observation

Why It Is Important / Effect on Geotechnical Analysis

- | | | |
|----------|---|--|
| 1 | Determines Depth of Groundwater Table | Accurate GWT depth is essential for computing effective stress, strength, and deformation. |
| 2 | Helps Estimate Seasonal Fluctuation | Rising/falling GWT affects bearing capacity, settlement, slope stability, and drainage design. |
| 3 | Essential for Effective Stress Calculations | Pore water pressure directly reduces effective stress → affects shear strength and bearing capacity. |
| 4 | Affects Soil Shear Strength | Saturated soil has lower shear strength; observation helps identify weak zones. |
| 5 | Important for Slope Stability Analysis | High pore pressure reduces stability; groundwater observations input into slope stability models. |
| 6 | Controls Consolidation & Settlement | Groundwater conditions influence compressibility and consolidation rate of clays. |
| 7 | Determines Seepage & Uplift Forces | High GWT creates upward seepage → potential uplift failure, piping, and erosion. |

Method of Groundwater observation

Rising water level method

This method most commonly referred to as the time log method which consists of boiling the water out of the casing and observing the rate of rise of the water level in the casing at intervals of time until the rise in water level becomes negligible.

From the figure; we have,

$$h_1 = H_0 - H_1$$

$$h_2 = H_1 - H_2$$

$$h_3 = H_2 - H_3$$

Let, $(t_1 - t_0) = (t_2 - t_1)$
 $= (t_3 - t_2) = \Delta t$

The depths H_0, H_2, H_3 of the water level in the casing from the normal water level can be computed as follows:

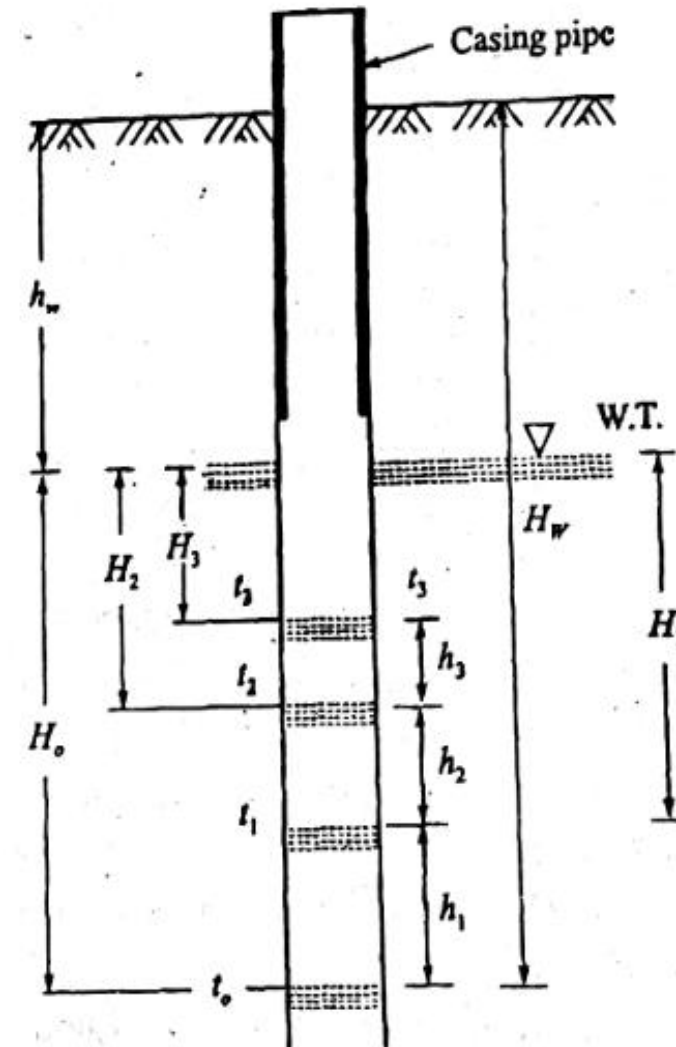


Figure: Rising water level method

Method of Groundwater observation

$$\left. \begin{aligned} H_0 &= \frac{h_1^2}{h_1 - h_2} \\ H_2 &= \frac{h_2^2}{h_1 - h_2} \\ H_3 &= \frac{h_3^2}{h_2 - h_3} \end{aligned} \right\}, \text{ etc.}$$

Let the corresponding depths of water table level below the ground surface be h_{w1} , h_{w2} , h_{w3} , etc.
Now, we have

$$h_{w1} = H_w - H_0$$

$$h_{w2} = H_w - (h_1 + h_2) - H_2$$

$$h_{w3} = H_w - (h_1 + h_2 + h_3) - H_3$$

where, H_w is the depth of water level in the casing from the ground surface at the start of the test.
Normally, $h_{w1} = h_{w2} = h_{w3} = h_w$; if not an average value gives h_w .

Casagrande Piezometer

Heading

Purpose

Components

Working Principle

Installation Steps

Description

To measure groundwater level and pore water pressure at specific depths.

- Porous tip (ceramic/plastic)
- PVC standpipe
- Sand filter around tip
- Bentonite/clay seal
- Grout/backfill

Water enters through the porous tip and rises in the standpipe until it equals the piezometric head at the tip depth.

1. Drill borehole to required depth
2. Place porous tip at target layer
3. Place sand filter around tip
4. Seal above with bentonite/clay
5. Install PVC pipe to surface
6. Backfill and cap the standpipe
7. Measure water level using indicator

Measurements Taken

- Groundwater table
- Pore water pressure
- Seasonal fluctuations

Advantages

- Simple and low-cost
- Reliable for long-term monitoring
- Easy to install and read

Limitations

- Slow response in low-permeability soils (clay)
- Cannot capture rapid pore pressure changes

Applications

- Slopes, embankments, dams
- Foundations and excavations
- Groundwater monitoring wells

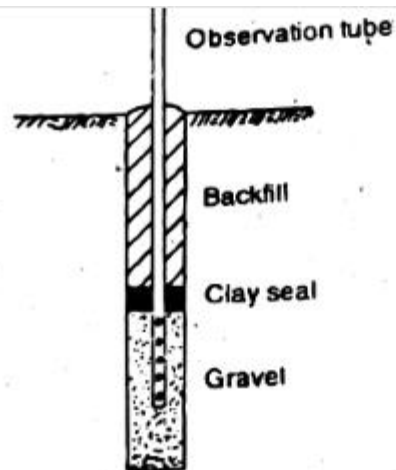


Figure: Piezometer for observation of GWL

Borehole Log

- Borehole logs are systematic records of all observations and measurements made during drilling of a borehole.
- They document soil layers, groundwater conditions, sampling, test results, drilling progress, and other relevant field details.
- Borehole logs are typically prepared by the site engineer or geologist during site investigation.

Importance

1. Understanding subsurface profile

2. Basis for geotechnical analysis

3. Identifies problematic soils

4. Locates groundwater table

5. Guides laboratory & field tests

6. Ensures construction safety

7. Documentation and verification

Explanation

Helps identify soil strata sequence, thickness, and variability, which is essential for foundation design.

Used to determine bearing capacity, settlement, slope stability, earth pressure, etc.

Detects weak layers, collapsible soils, expansive clays, peat, organic soils.

Provides GWT depth, fluctuations, and artesian conditions crucial for excavation and dewatering.

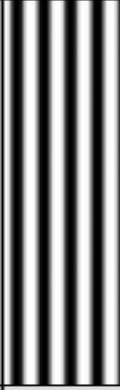
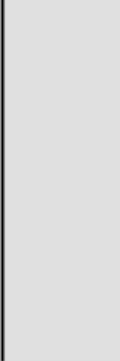
Ensures correct selection of samples for testing (SPT, permeability tests, triaxial tests).

Helps in assessing risks like liquefaction, landslides, or differential settlement.

Acts as a permanent record for future design, comparison, and legal documentation.

MULTI Lab (P) Ltd.
BORE HOLE LOG

Project	:	Soil Investigation of National College of Engineering Building
Location	:	Talchhikhel, Lalitpur
Bore Hole No	:	2
Diameter of BH, mm	:	150 mm
RL of GWT	:	6.00 m
Date	:	28th Jan, 2024 to 29th Jan, 2024
Logged By	:	Surya Tamang
Prepared By	:	Manoj Subedi
Checked By	:	Sandeep Kr. Jha
Certified By	:	Madhusudan K.C.

Scale 1=50cm Each	Depth	Thickness	Sampling		Soil Classification	Group Symbol	Soil Symbol	SPT (Field Record)			Value N
	m	m	Depth m	Type				15 cm	30 cm	45 cm	
	0.00	1.50			Filling materials including sandy silt with gravels & pieces of bricks	FM					
	1.50		1.50	SPT				4	4	5	9
		2.30			Gray to brown clayey silt of low plasticity	ML					
	3.80		3.00	SPT				3	4	5	9
		3.20			Gray clayey silt of medium plasticity	MI					
			4.50	SPT				3	4	6	10
			5.50	UDS							
	7.00		6.00	SPT				3	4	7	11
		11.50			Gray to white clayey silt of low plasticity	ML					
			7.50	SPT				4	7	9	16
			9.00	SPT				4	8	8	16
			10.50	SPT				7	9	11	20
			12.00	SPT				6	9	12	21
			13.50	SPT				7	10	12	22
			15.00	SPT				6	11	12	23
			16.50	SPT				7	10	12	22
	18.50		18.00	SPT				6	11	12	23
		11.50			Gray to white silty sand with formation of mud stone & sand stone	na					
			19.50	SPT				12	25	20	45
			21.00	SPT				18	22	24	46
			22.50	SPT				17	>50	-	>50
			24.00	SPT				20	-	-	>50
			25.50	SPT				>50	-	-	>50
			27.00	SPT				>50	-	-	>50
			28.50	SPT				>50	-	-	>50

Component of Borehole Log

- Borehole number and grid reference
- Drilling method: rotary, percussion, auger
- Start–end depth of each layer
- Soil classification using USCS or BS
- SPT N-values at each test depth
- Sample ID, depth, and type
- Water table rise/fall during drilling
- Stratigraphic sketch (with symbols)

Geophysical tests

1. Geophysical tests are non-invasive subsurface investigation methods that measure the physical properties of soil and rock (such as electrical resistivity, seismic velocity, magnetic response) to interpret subsurface conditions without excavation or drilling.
2. These methods are widely used for:
 - Rapid site investigation
 - Mapping soil/rock layers
 - Groundwater detection
 - Detecting weak zones, cavities, boulders
 - Seismic hazard studies

Geophysical tests

Importance

Why It Matters

Non-destructive

No drilling needed; preserves site conditions.

Covers large areas quickly

Faster and cheaper than boreholes for preliminary studies.

Identifies subsurface anomalies

Detects cavities, faults, boulders, buried utilities.

Supports geotechnical design

Provides shear wave velocity, dynamic soil properties, stratigraphy.

Improves accuracy

Used together with boreholes to refine soil model.

Types of Geophysical tests

- **Seismic Methods**
 - Seismic Refraction
 - Seismic Reflection
 - MASW (Multichannel Analysis of Surface Waves)
 - SASW (Spectral Analysis of Surface Waves)
- **Electrical Methods**
 - Electrical Resistivity (ERT)
 - Vertical Electrical Sounding (VES)
 - Resistivity Tomography
- **Electromagnetic Methods**
 - Ground Penetrating Radar (GPR)
 - FDEM (Frequency/Time Domain Electromagnetic)
- **Gravity Method**
- **Magnetic Method**
- **Remote Sensing / Georadar**
 - Gravity Survey
 - Magnetic Survey
 - Satellite Imaging • Aerial/Drones

Seismic method

- **Principle**

Uses propagation of seismic waves (P-waves & S-waves) through soil/rock to determine subsurface properties.
- **Types**
 - Seismic Refraction
 - Seismic Reflection
 - MASW (Multichannel Analysis of Surface Waves)
 - ReMi
 - Cross-Hole / Down-Hole / Up-Hole
- **Main Purpose**

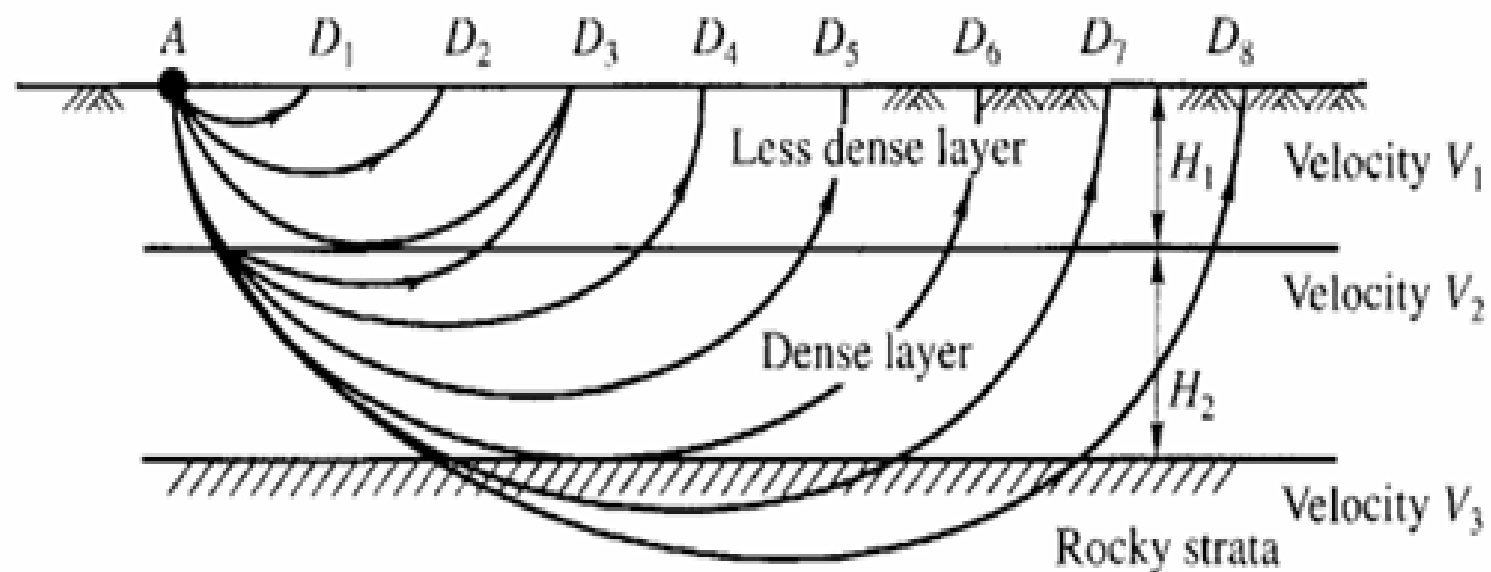
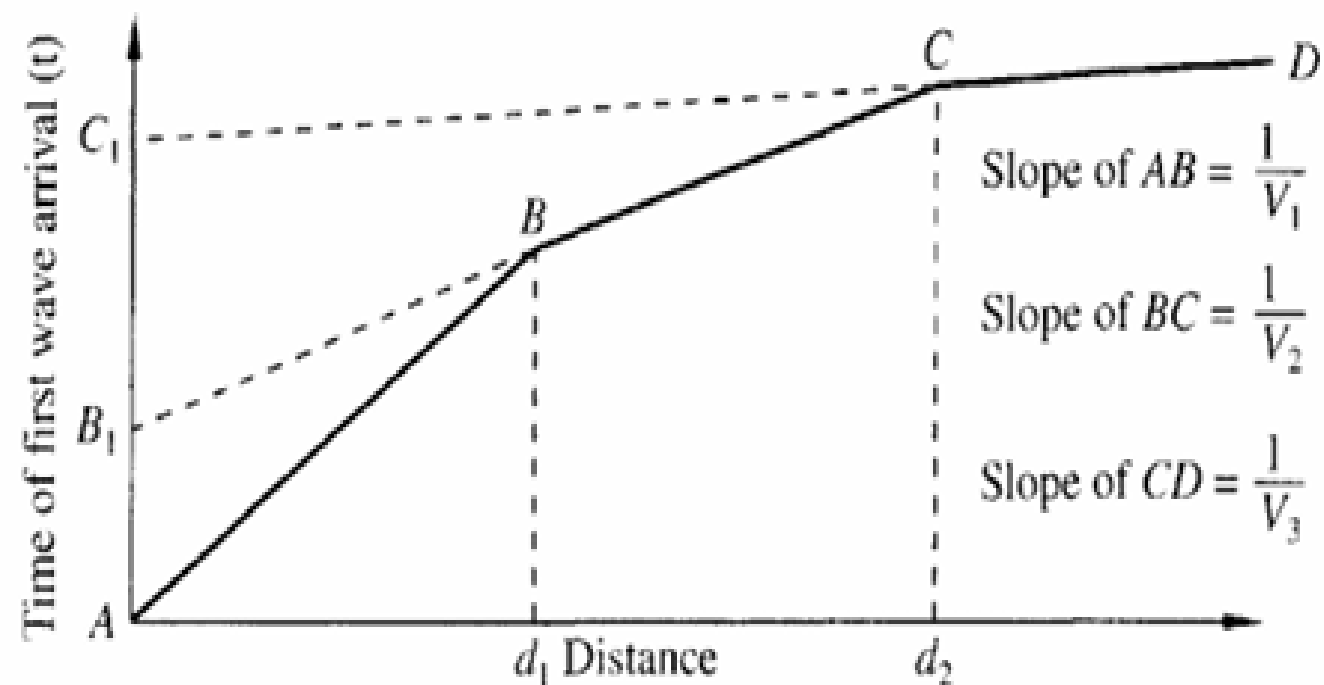
To estimate stiffness, depth of layers, bedrock profile, shear-wave velocity, and dynamic soil properties.
- **Key Measurements**

Travel time of waves, wave velocity (V_p , V_s), layer thickness, dynamic moduli.

 - Non-destructive
 - Covers a large area
 - Good for depth to bedrock
 - Useful for dynamic site characterization.
- **Advantages**
 - Requires good coupling on ground
 - Noise sensitive
 - Difficult in highly heterogeneous soils.
- **Limitations**

Seismic method procedure

- Select the test line and prepare the ground.
- Place **geophones** at required spacing.
- Set up the seismograph and check noise levels.
- Position **seismic source** (hammer/weight drop).
- Generate seismic waves (shot).
- Record **arrival times** at geophones.
- Repeat shots for accuracy.
- Process data to obtain velocities (**V_p , V_s**).
- Interpret layer thickness, stiffness, and bedrock depth.

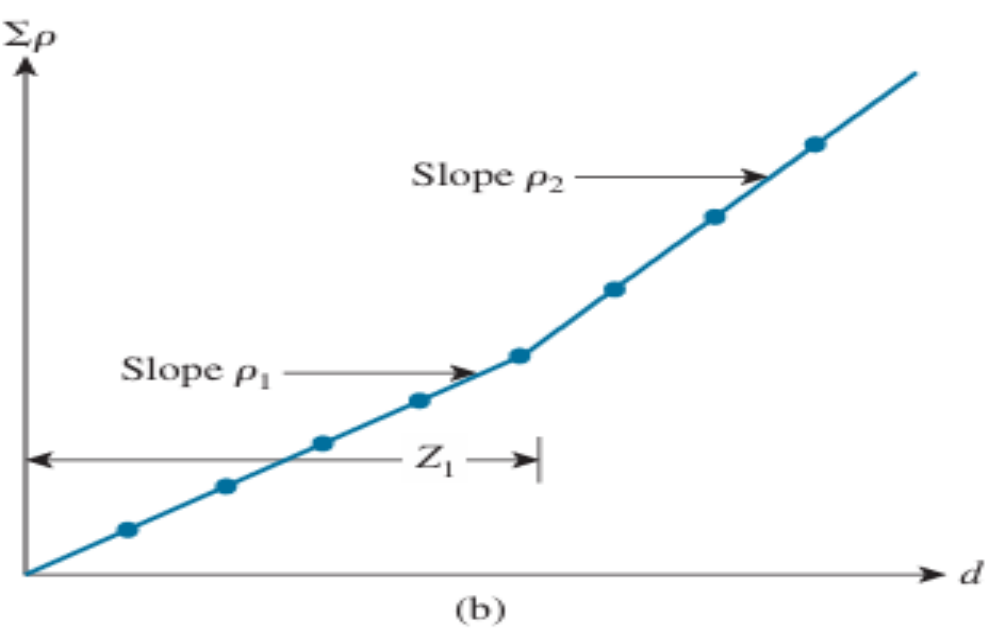
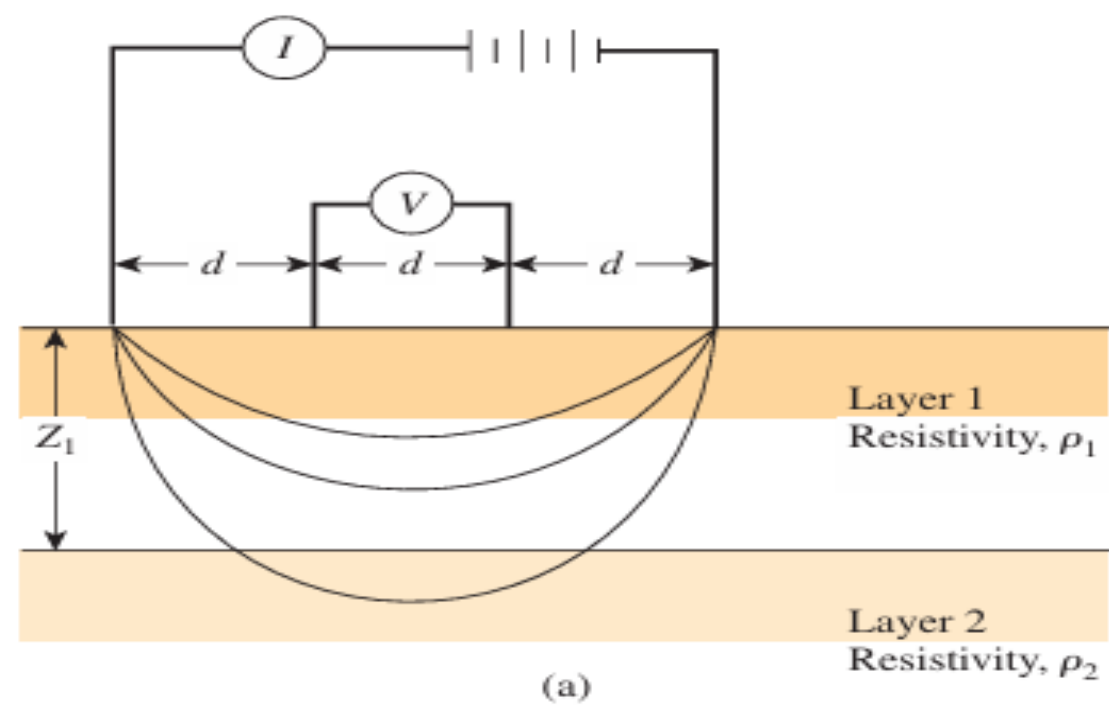


Electrical method

Principle	Measures electrical resistivity of soil/rock by injecting current into the ground.
Common Methods	• Electrical Resistivity Tomography (ERT) • Wenner Array • Schlumberger Array
Purpose	To identify subsurface layers, groundwater, voids, bedrock depth, and contamination zones.
Advantages	• Simple and economical • Good for groundwater detection • Non-destructive.
Limitations	• Slow for long lines • Affected by dry/hard ground • Interpretation may be non-unique.

Electrical method procedure

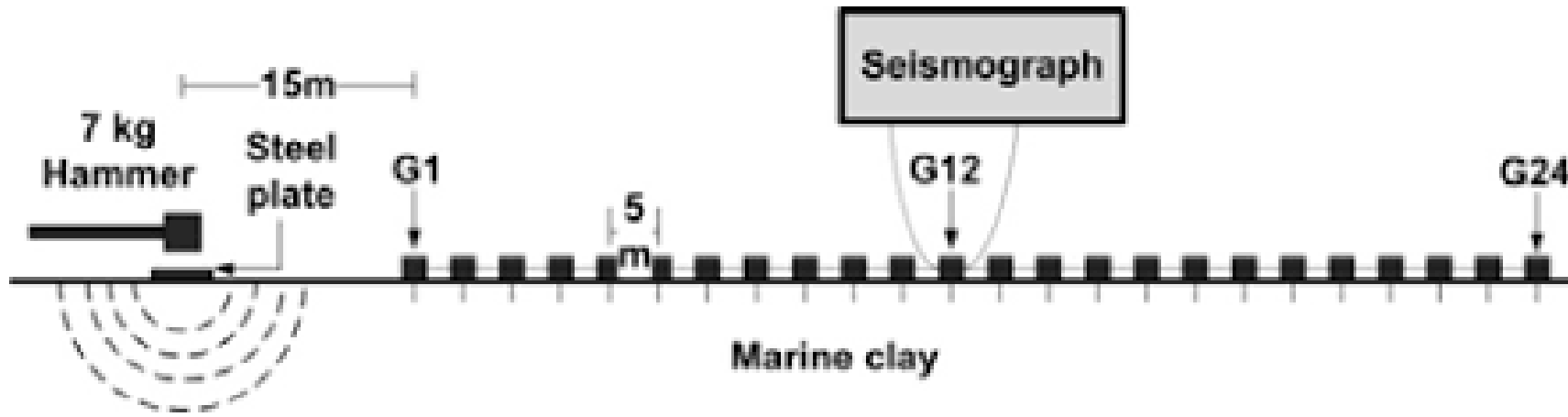
- Select survey line and determine electrode spacing.
- Place **electrodes** (current and potential) in the ground.
- Connect all electrodes to the **resistivity meter**.
- Inject current into the ground through current electrodes.
- Measure voltage difference using potential electrodes.
- Record current, voltage, and apparent resistivity values.
- Increase electrode spacing to explore deeper layers.
- Repeat measurements along the line.
- Process data to generate resistivity profile.
- Interpret subsurface layers, groundwater, or bedrock.



MASW(Multichannel Analysis of Surface Waves)

- **Full Form** Multichannel Analysis of Surface Waves
- **Purpose** Determine shear wave velocity (V_s) profile of soil/rock using Rayleigh waves
- **Key Output** V_s (shear wave velocity)–depth profile, stiffness profile, site classification
 - Site characterization
 - Liquefaction assessment
 - Seismic analysis
 - Ground improvement evaluation
- **Applications**
 - Non-invasive
 - Fast field data collection
 - Cost-effective
 - Works well in noisy urban areas
- **Merits**
 - Limited depth (~20–40 m typical)
- **Demerits**
 - Sensitive to high-contrast layers
 - Requires experienced processing

MASW(Multichannel Analysis of Surface Waves)

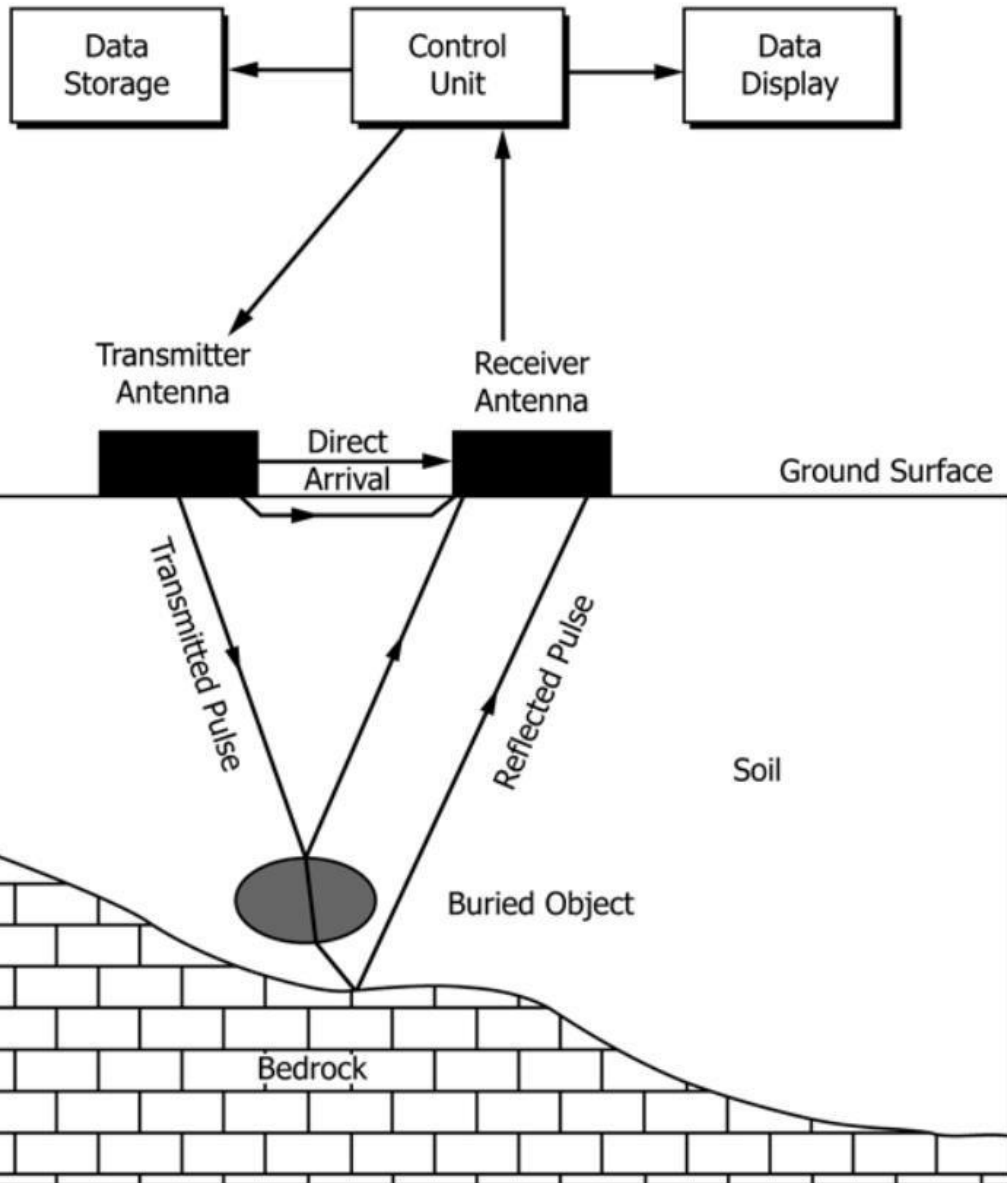


- **Lay out geophones** in a straight line with equal spacing and connect to the seismograph.
- **Generate surface waves** using a hammer or weight drop at one or more shot points.
- **Record wave signals** from all channels and check data quality.
- **Extract dispersion curves** (phase velocity vs frequency) from the recorded wavefield.
- **Perform inversion** to convert the dispersion curve into Vs–depth profile.
- **Interpret** the Vs profile to identify soil layers and site characteristics.

Ground Penetrating Radar

Full Form	Ground Penetrating Radar
Purpose	Detect subsurface features using high-frequency electromagnetic waves
Key Output	Radargrams showing depth and location of buried objects/layers
Applications	• Utility detection • Pavement evaluation • Void detection • Rebar/RC mapping • Archaeology • Soil/strata layering
Merits	• Quick, non-destructive • High resolution (shallow depth) • Works on pavements & concrete
Demerits	• Limited depth in wet/clayey soils • Requires skilled interpretation • Metal interference possible

Ground Penetrating Radar procedure



- **Select antenna frequency** based on required depth and resolution.
- **Mark survey lines** or a grid on the ground surface.
- **Move the GPR antenna** smoothly along each line while collecting data.
- **Record radar reflections** from subsurface features in real time.
- **Process the data**
- **Interpret radargrams** to identify layers, utilities, voids, or buried objects.

Gravity method

Purpose

- To measure variations in the Earth's gravitational field caused by density differences in subsurface rocks.

Output

- Gravity anomaly maps
- 2D/3D subsurface models indicating structural variations.

Applications

- Mineral exploration (e.g., sulfide deposits, iron ore).
- Hydrocarbon exploration (mapping basins and salt domes).
- Groundwater studies.
- Geotechnical and engineering site investigations.

Merits

- Non-destructive and environmentally friendly.
- Relatively low operational cost.
- Rapid data collection over large areas.

Demerits

- Poor resolution for small or deep targets.
- Ambiguity in interpretation (different models may explain same anomaly).
- Requires corrections for terrain, latitude, elevation, etc.
- Sensitive to noise and environmental factors.

Gravity method procedure

- Select survey area and set up base station.
- Take gravity readings at each station from **gravimetry**.
- Measure elevation and location of stations.
- Apply corrections (drift, latitude, free-air, Bouguer, terrain).
- Calculate gravity anomalies.
- Prepare maps and interpret subsurface structures.

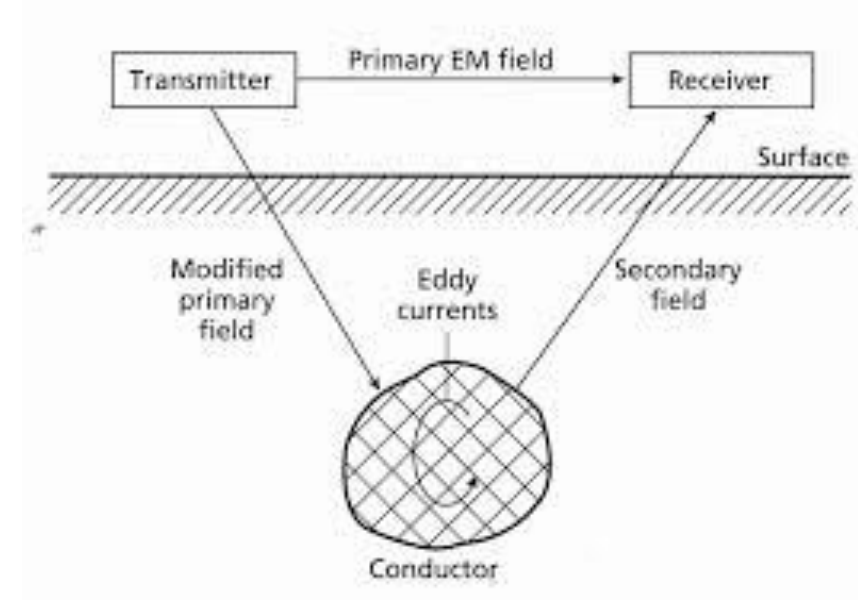


Magnetic method

Purpose	Detect variations in the Earth's magnetic field caused by subsurface rocks or buried objects.
Output	Magnetic anomaly maps showing intensity variations
Applications	Mineral exploration (iron ores, magnetite), mapping geologic structures, locating buried pipes/UXO, archaeological surveys.
Merits	• Fast and cost-effective • Covers large areas • Non-invasive • Works from ground, air, or marine.
Demerits	• Cannot detect non-magnetic materials influenced by cultural noise (vehicles, fences, power lines) • Interpretation is non-unique • Requires corrections (diurnal, elevation).

Magnetic method procedure

- Set up and calibrate the magnetometer.
- Lay out survey lines/grid.
- Measure magnetic readings at each station.
- Record base-station readings.
- Check data quality and repeat questionable readings.
- Identify anomalies, estimate depth/geometry, and correlate with geology.
- Prepare maps and interpret subsurface structures.



Evaluation of liquefaction potential

Liquefaction-definition

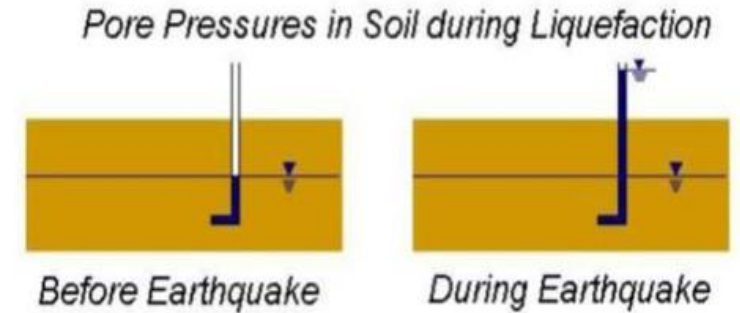
Factors affecting liquefaction (Parameters required for liquefaction evaluation)

Methods of LP evaluation

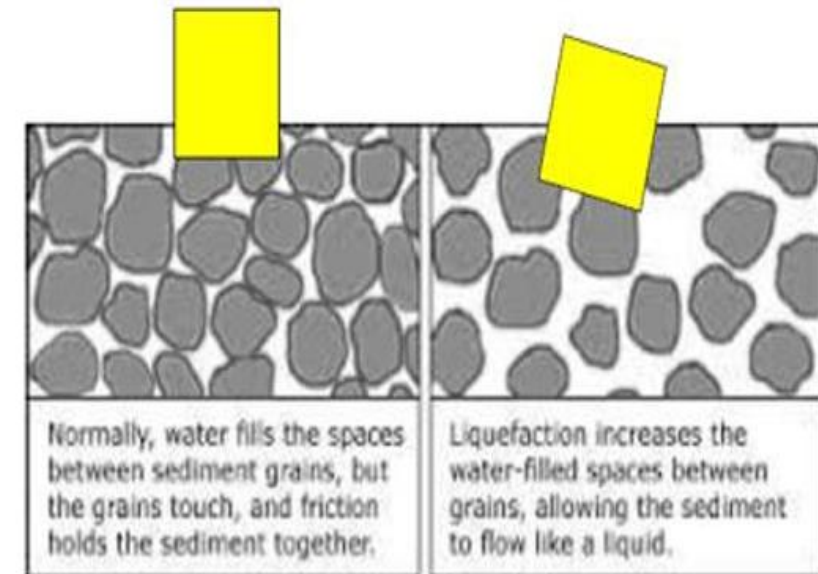
Numerical example

Liquefaction

- Liquefaction is a phenomenon in which saturated, loose, cohesionless soils (mainly sands and silts) lose strength and stiffness and start behaving like a liquid when subjected to cyclic or dynamic loading, such as earthquake shaking.
- This occurs because pore water pressure increases and becomes equal to or greater than effective stress, causing the soil skeleton to collapse.

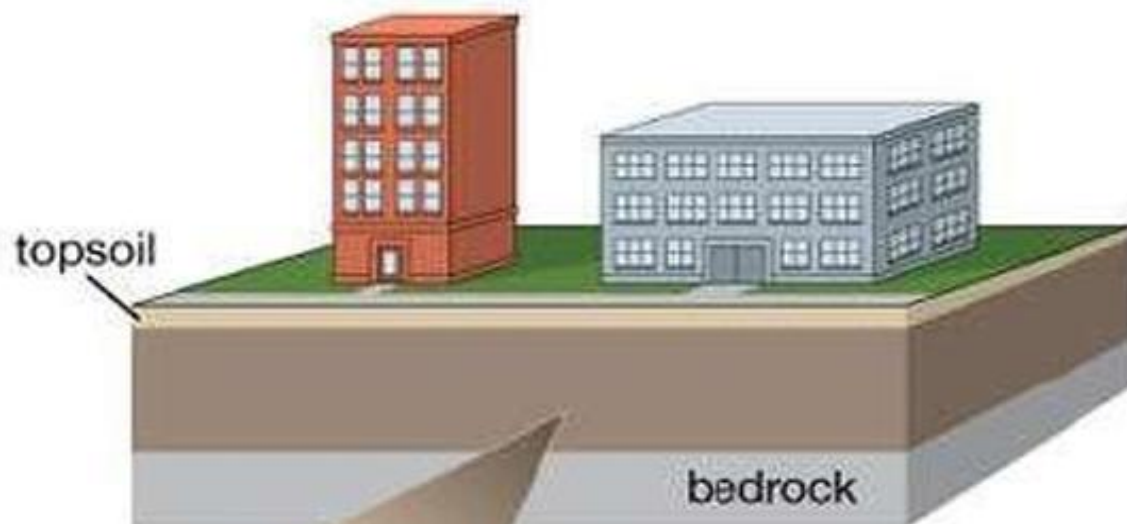


Response of sandy, loose soil with a shallow water table during an earthquake. (University of Bristol web site)



Soil liquefaction

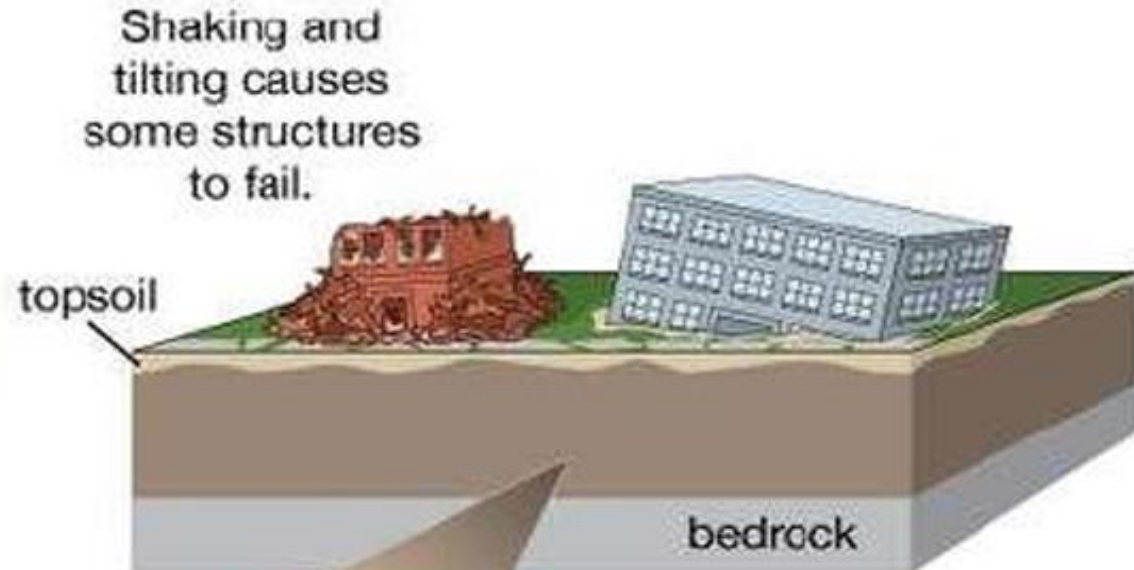
stable soil



Building stands erect
on stable soil.

Loosely packed grains
of soil are held together
by friction. Pore spaces
are filled with water.

liquefied soil

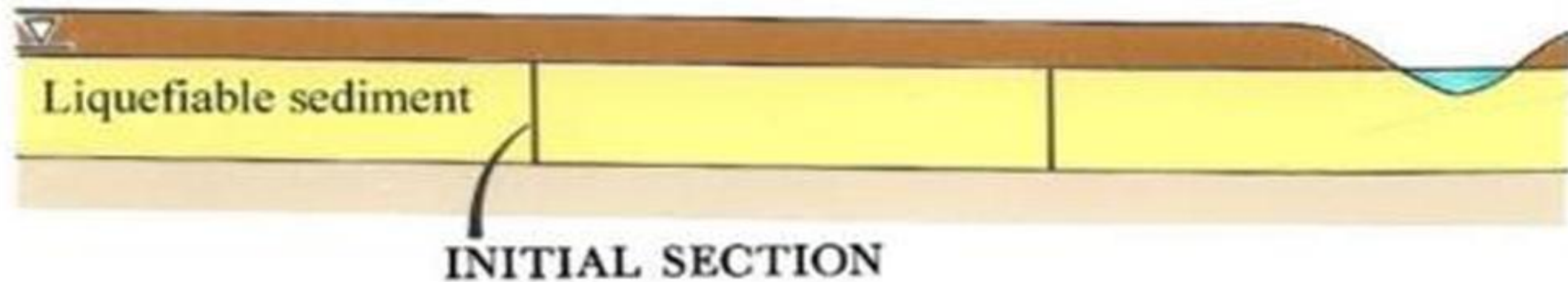


Building tilts
and sinks as
soil stability
declines.

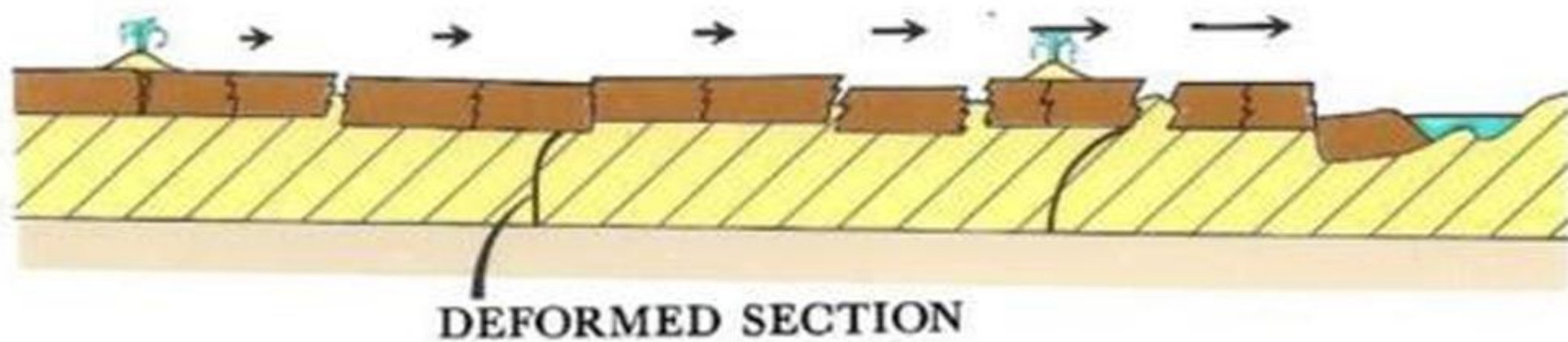
Shaking destabilizes
the soil by increasing the
space between grains.
With its structure lost,
the soil flows like a liquid.

LATERAL SPREAD

Before earthquake:



After earthquake:



Factors affecting liquefaction

- **Soil Properties**
 - Soil type
 - Loose sands & silty sands are most susceptible.
 - Relative density
 - Lower density → higher liquefaction potential.
 - Grain size
 - Uniform sands more prone; well-graded less prone.
 - Fines content
 - Intermediate fines may increase susceptibility.
 - Plasticity
 - Non-plastic silts liquefy; plastic soils do not.
- **Groundwater & Saturation**
 - Groundwater table depth
 - Shallow GWT increases risk.
 - Degree of saturation
 - Full saturation required for liquefaction.
- **Stress Conditions**
 - Effective stress
 - Lower effective stress → easier liquefaction.
 - Overburden pressure
 - Higher confining stress reduces liquefaction.

• Earthquake Loading	Magnitude	Larger magnitude → more cycles → higher potential.
	Peak Ground Acceleration (PGA)	Higher PGA → higher cyclic stress.
	Duration of shaking	Longer duration increases pore pressure buildup.
• Geological Factors	Age of deposit	Younger, uncemented soils are more vulnerable.
	Depositional environment	Fluvial/alluvial/reclaimed soils more susceptible.
• In-Situ Test Parameters	SPT-N value	Higher N-value → higher resistance.
	CPT-qc value	Higher cone resistance → lower susceptibility.
	Shear wave velocity (V_s)	Higher V_s → stiffer soil → less liquefaction.

Liquefaction Calculation

1. **Demand (CSR):** Compute field cyclic stress ratio from seismic loading (PGA, magnitude, depth reduction factor),

$$CSR = \frac{\tau_{\max}}{\sigma'_{v0}} \quad \text{or} \quad CSR = 0.65 \frac{a_{\max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} r_d.$$

$a_{\max}$ = peak horizontal ground surface acceleration

g = Acceleration due to gravity

σ_v = Total vertical stress

$\sigma_{v'}$ = Effective vertical stress

M_w = earthquake moment magnitude.

r_d = soil shear mass participation factor

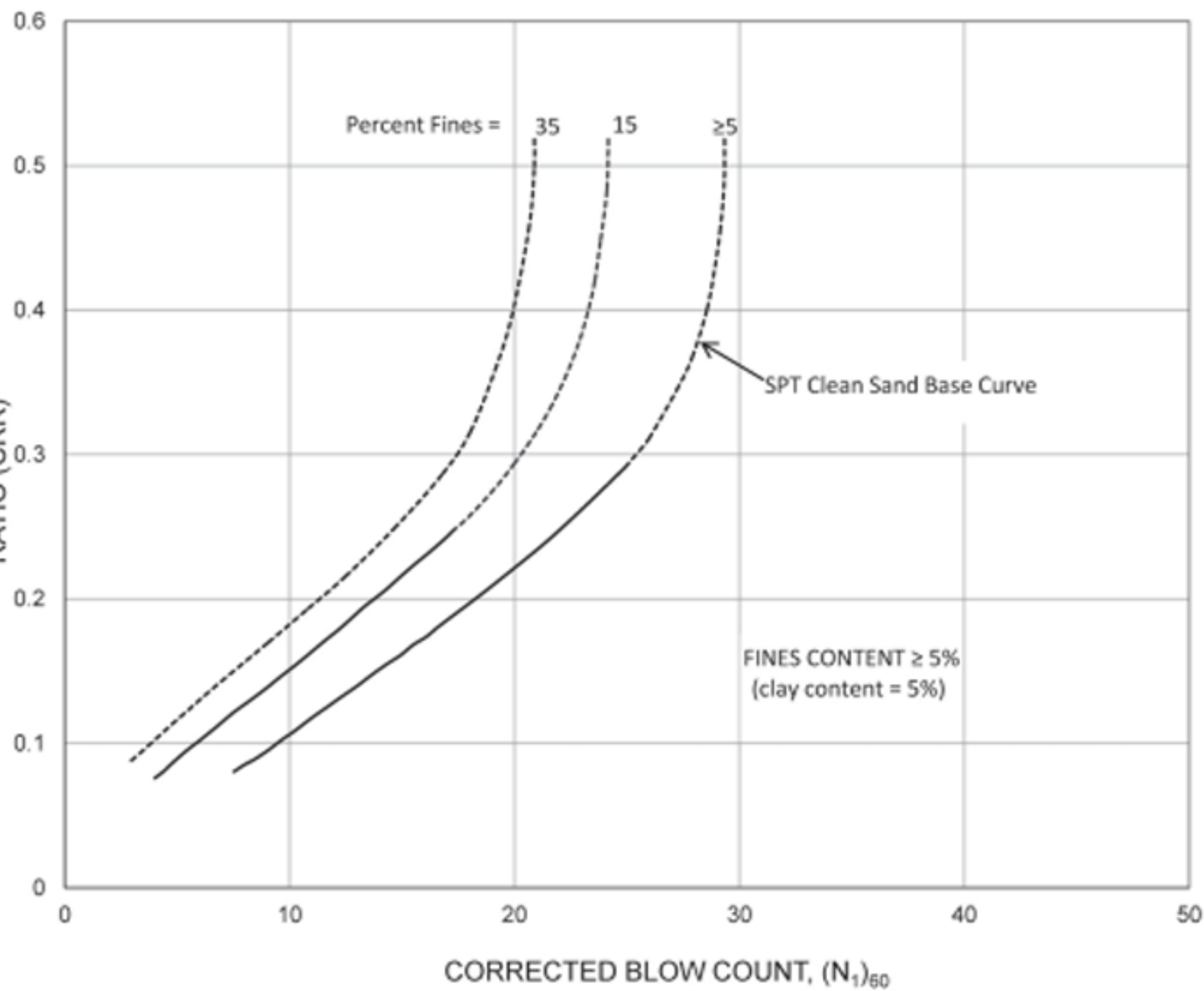
2. **Capacity (CRR):** Obtain from in-situ indices (SPT $N_{1,60}$, CPT $(q_c)_1N$, VS) or from calibrated cyclic laboratory tests for the site soils.
3. **Factor of safety and pore-pressure expectation:**

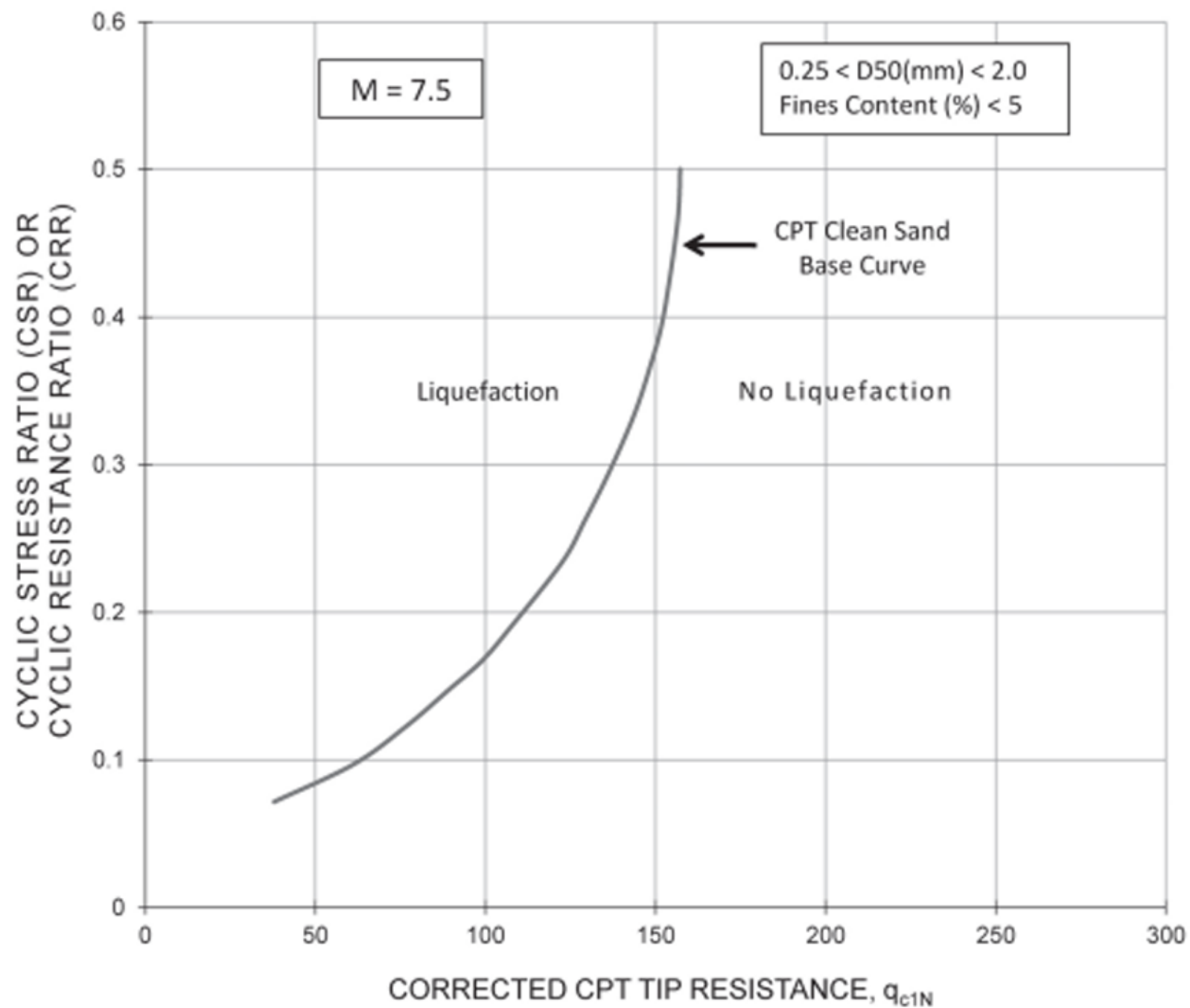
$$FS(z) = \frac{CRR(z)}{CSR(z)}$$

If $FS < 1$, the soil is expected to generate excess pore pressure rapidly; corresponding laboratory r_u –CSR relationships anticipate $r_u \rightarrow 1$ within the expected number of cycles.

4. **Site-level severity:** Integrate $FS(z)$ over depth to compute **LPI (or LSN)** to assess the likelihood and severity of surface manifestations (settlement, sand boils, lateral spreading).
5. **Decision:**
 - **Low risk:** $FS \geq 1.1$ over depth and $LPI < 5$.
 - **Potentially liquefiable:** zones with $FS < 1$ and LPI 5–15.
 - **High risk:** widespread $FS < 1$ and $LPI > 15 \rightarrow$ ground-improvement or design mitigation warranted.

CYCLIC STRESS RATIO (CSR) OR CYCLIC RESISTANCE
RATIO (CRR)





METHODS OF REDUCING SOIL LIQUEFACTION HAZARDS

- **Compaction of Loose Sands**
- **Driving of piles**
- **Grouting and Chemical Stabilization:**

A mixture of cement and water, with or without sand, is the most common grout.

- **Sand Drain**
- **Stone Column**

EFFECTS OF LIQUEFACTION

- **Alteration of Ground Motion**
- **Settlement**
- **Instability**
- **Development of Sand Boils**